Evolution of a Humid Tropical Landscape in Northcentral Costa Rica as Deduced from Geomorphic and Pedogenic Evidence

by Anke Maria Neumann Wells

Diplom, Deutsche Sporthoschschule Köln, 1963

M. A., University of Kansas, 1965

Professor in Charge
Wakefield Dort Jr.

Committee Members
Curtis J. Sorensen
Robert E. Nunley

EVOLUTION OF A HUMID TROPICAL LANDSCAPE IN NORTHCENTRAL COSTA RICA AS DEDUCED FROM GEOMORPHIC AND PEDOGENIC EVIDENCE

ANKE MARIA NEUMANN WELLS

1979

EVOLUTION OF A HUMID TROPICAL LANDSCAPE IN NORTHCENTRAL COSTA RICA AS DEDUCED FROM GEOMORPHIC AND PEDOGENIC EVIDENCE

by

Anke Maria Neumann Wells
Diplom, Deutsche Sporthochschule Köln, 1963
M.A., University of Kansas, 1965

Submitted to the Department of Geography and Meteorology, and the Faculty of the Graduate School of the University of Kansas in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

Dissertation Committee:

Wakefield Dort Jr.
Chairman

Curtis J. Sorenson

Robert J. Munday

Dissertation defended: January 1979

TO MY PARENTS

ABSTRACT

Progressive landscape changes in humid tropical provinces of southern San Carlos Canton in northcentral Costa Rica can be attributed to tectonic, volcanic, mass-wasting, and fluvial events. Spatial distribution of principal landform types and variations in degree of soil development of associated modern and buried soils are used to determine major episodes of landscape evolution. The two lines of evidence complement each other in that pedogenic evidence permits an assessment of temporal relationships between spatially disjunct landforms and of the magnitude of age differences between landforms, information unattainable from geomorphic evidence alone.

Small hills of laharic origin, alluvial plains, and paired terraces are present in the Atlantic Lowland Province of southern San Carlos. The Piedmont Province contains tilted fault-block ridges, alluvial/laharic fans, alluvial plains, cinder cones, and volcanic ash mantles. Spatial segregation of differing landform types prevents assessment of relative landform ages for the region as a whole.

Duration of soil formation has exerted the greatest influence on pedogenesis; hence, degree of soil development provides a qualitative measure of soil age. Differences in

soil development are revealed by silt/clay ratios, soil texture, free iron-oxide content, soil color, and illuvial-clay content, in order of decreasing usefulness. Soils at an early, at an intermediate, and at an advanced stage of soil development are recognizable; ranking of individual soil groups within general age categories is possible on the basis of silt/clay ratios and soil texture. Absolute soil ages are inferred from silt/clay ratios in subsoil horizons. Knowledge of relative landform ages is greatly enhanced by pedogenic evidence.

Pliocene tectonism, accompanied by explosive volcanic activity and laharic deposition, led to formation of four cinder cones in the eastcentral part of the Piedmont Province and small hills of laharic origin in the Atlantic Lowland Province of southern San Carlos. Further tectonism during the early Pleistocene created three tilted fault-block ridges in the western and central parts of the Piedmont Province. Consequent increase in fluvial aggradation initiated formation of alluvial plains in the Piedmont and Atlantic Lowland Provinces and, aided by intermittent laharic deposition, caused the buildup of alluvial/laharic fans against the backslopes of tilted fault-block ridges. Upper portions of most alluvial/laharic landforms are late Pleistocene, those of alluvial plains in the Atlantic Lowland Province Recent in age. Explosive volcanic activity during the middle Pleistocene and late Holocene is responsible for pyroclastic surface deposits in the northeastern and southeastern parts of the Piedmont Province, respectively. The more recent volcanic event possibly took place at the time when increased fluvial degradation led to formation of paired terraces in the Atlantic Lowland Province of the region.

TABLE OF CONTENTS

Page

LIST OF TABLES

Table		Page
12.	Presence of Argillans in Subsoil Horizons of Paleosols in Southern San Carlos	142
13.	Color Hues of A Horizons and Reddest Color Hues and Strongest Chromas of B2 Horizons of Paleosols in Southern San Carlos	145
14.	Free Iron-Oxide Content of B2 Horizons of Paleosols in Southern San Carlos	147
15.	Paleosols in Southern San Carlos Ranked According to Differences in Degree of Soil Development Established on the Basis of Differences in Pedogenic Properties	150
16.	Percentages of Free Iron Oxides of Different Size Fractions of a Clay Soil	235
17.	Soils on Small Hills of Laharic Origin in the Atlantic Lowland Province	245
18.	Soils on Alluvial Plains in the Atlantic Lowland Province	247
19.	Soils on Tilted Fault-Block Ridge I in the Piedmont Province	248
20.	Soils on Tilted Fault-Block Ridge II in the Piedmont Province	250
21.	Soils on Tilted Fault-Block Ridge III in the Piedmont Province	253
22.	Soils on Alluvial/Laharic Fans in the Piedmont Province	255
23.	Soils on Cinder Cones and Associated Pyroclastic Deposits in the Piedmont Province . .	257

LIST OF ILLUSTRATIONS

Figure		Page

ACKNOWLEDGEMENTS

I am indebted to many persons who assisted me during the course of my study. My deepest gratitude is expressed to Dr. Wakefield Dort, Jr. for his helpful comments and suggestions on several versions of the manuscript, but most of all for his continuing encouragement and support which enabled me to successfully complete the study. I am also very grateful for the valuable advice given by Dr. Curtis J. Sorensen on the part of the study dealing with soils, and for the assistance provided by Dr. Robert E. Nunley in editing the final manuscript. Drs. Roger Kaesler, George F. Jenks, and Glen A. Marotz are thanked for serving as members of the final examination committee. My sincere thanks are expressed to several other persons who contributed to the progress of the study: Dr. Stuart A. Harris who suggested the problem and assisted with initial field and laboratory work; Dr. David S. Simonett who as interim chairman of the dissertation committee provided field assistance and photographic equipment and supplies through the Center for Research, Inc.; Dr. Stanley A. Morain who briefly served also as interim chairman of the dissertation committee; Mr. Allen Penny who performed some of the laboratory analyses; Dr. Norman Carpenter who gave advice on the cartographic work; and Ms. Sharon K. Hagen who aided in dry-mounting of photographs. I am also very thankful for the assistance I received during my stay in Costa Rica: Mr. Jorge Campabadal and his staff at the Costa Rican office of the Organization for Tropical Studies, Inc. supplied equipment and assisted in the packaging and transport of soil samples; Dr. Enrique Malavassi V. aided in the interpretation of the geology of the study area; Mr. Ralph Miller and his family provided a home at the Centro Rural Metodista in Tessalia during the time of my field work; on occasion, I also enjoyed the hospitality in the homes of would-be friends Ofelia Castro Cordero and Carmen Alpízar Castro; Gerado was my faithful and hard-digging field assistant. Very special thanks are expressed to my husband Phil and my son Axel for their patience and love, and to my friends Jennie Dienes and Louise McClendon for moral support and child care. Phil is also thanked for some professional advice and financial assistance, Jennie for checking English style and grammer in the first two chapters of the dissertation. Financial support for the field work in Costa Rica was provided by the Organization for Tropical Studies, Inc.; some travel funds were granted by the Graduate School of the University of Kansas.

CHAPTER I

INTRODUCTION

Landscape Episodicity and Homogenization in the Humid Tropics

Most regions of the world, including the humid tropics, have not been stable throughout their existence, but have experienced episodes of landscape instability which resulted from major changes in climate and/or geologic events. In the humid tropics, landscape instability caused by volcanic activity and tectonic movements has occurred at all elevations. In contrast, landscape instability due to changes in climate appears to have been most pronounced at higher altitudes. Although snowline depressions seem to indicate cooler and moister climatic conditions in the humid tropics during Pleistocene glacial ages (e.g. Hastenrath, 1967a, p. 549; Wilhelmy, 1957, p. 302), humid tropical lowlands are generally thought to have experienced a climate not much different from that of today because climatic and vegetational zones apparently shifted downward much less at lower than at higher elevations (Wilhelmy, 1957, p. 303-304, 307). Evidence provided for glacial-age aridity in humid tropical lowlands, especially in the Americas (e.g. Bigarella and Andrade, 1965; Damuth and Fairbridge, 1970; Haffer, 1969; Viulleumier, 1971), is too fragmentary and speculative to convincingly prove otherwise.

During periods of landscape instability, major landscape changes take place. Erosion and deposition tend to be rapid and of great magnitude, causing the alteration or destruction of preexisting landforms and the creation of new landforms, and the truncation and the burial of soils (Butler, 1959, p. 5). During intervening periods of relative landscape stability, weathering and soil development predominate on landform surfaces because erosion and deposition are relatively slow and of small magnitude (Butler, 1959, p. 5). The degrees of landform alteration and pedogenesis which are attained during stable periods depend greatly on climate, as recognized by the concept of morphogenetic regions (Büdel, 1950, 1963; Peltier, 1950; Leopold et al., 1964).

In humid tropical lowlands, where mean annual temperatures and precipitation are high, the alteration of landforms and the formation of soils proceed rapidly during periods of relative landscape stability. Geomorphic and pedogenic processes are of great intensity. They also act upon the landscape continuously since, in the absence of cold and pronounced dry seasons, there are no periods of relative quiescence during which their action is diminished. Despite this tendency toward landscape homogenization, landscape changes produced during geologically unstable periods are distinguishable, provided that episodes of landscape instability occurred during the recent geologic past and that successive episodes of landscape instability were separated by sufficiently long intervals of time to allow the development of diagnostic pedogenic properties on landform surfaces.

Purpose of Study

The purpose of this study is to determine major episodes of landscape evolution in a humid tropical region of low elevation and recent geologic age in which landscape instability resulted mainly from recurrent tectonism and intermittent volcanic activity. Progressive landscape changes are deduced from geomorphic and pedogenic evidence: (1) spatial distribution of principal landform types in the region; and (2) variations in the degree of soil development of modern and buried soils formed on the differing landform types. The two lines of evidence complement each other in that pedogenic evidence permits an assessment of temporal relationships between spatially disjunct landforms and of the magnitude of age differences between landforms, information unattainable from geomorphic evidence alone.

Chapter Organization

In the remainder of Chapter I. the location, geology, climate, and vegetation of the study area are described and general effects of climate and vegetation on geomorphic and pedogenic processes in the study area are pointed out.

In Chapter II, principal landform types in the study area are described, the origin and spatial distribution of landforms are discussed, and information about relative ages of landforms which can be obtained from their spatial distribution is provided.

In Chapter III, the temporal distribution of modern and buried soils in the study area is treated. After a summary of the nature of and variations in soil-forming factors in the study area, relative ages of soils are assessed with the aid of hypothesized relationships between selected pedogenic properties and degree of soil development.

In Chapter IV, major results from landform and soil studies are stated, inferences from soil studies about the temporal distribution of landforms are discussed, and major episodes of landscape evolution in the study area are outlined.

Location of Study Area

The study area is located in northcentral Costa Rica at 10°N latitude and 84°W longitude. It occupies lowland and piedmont portions in the southern part of the Canton of San Carlos in the Province of Alajuela (Fig. 1). The irregular boundaries of the study area, referred to as southern San Carlos, are approximately defined as follows: a north-south line, extending between the villages of Pital and Venecia, in the east; margins of lobate lava flows, which form the northern boundary of the Mountainous Province

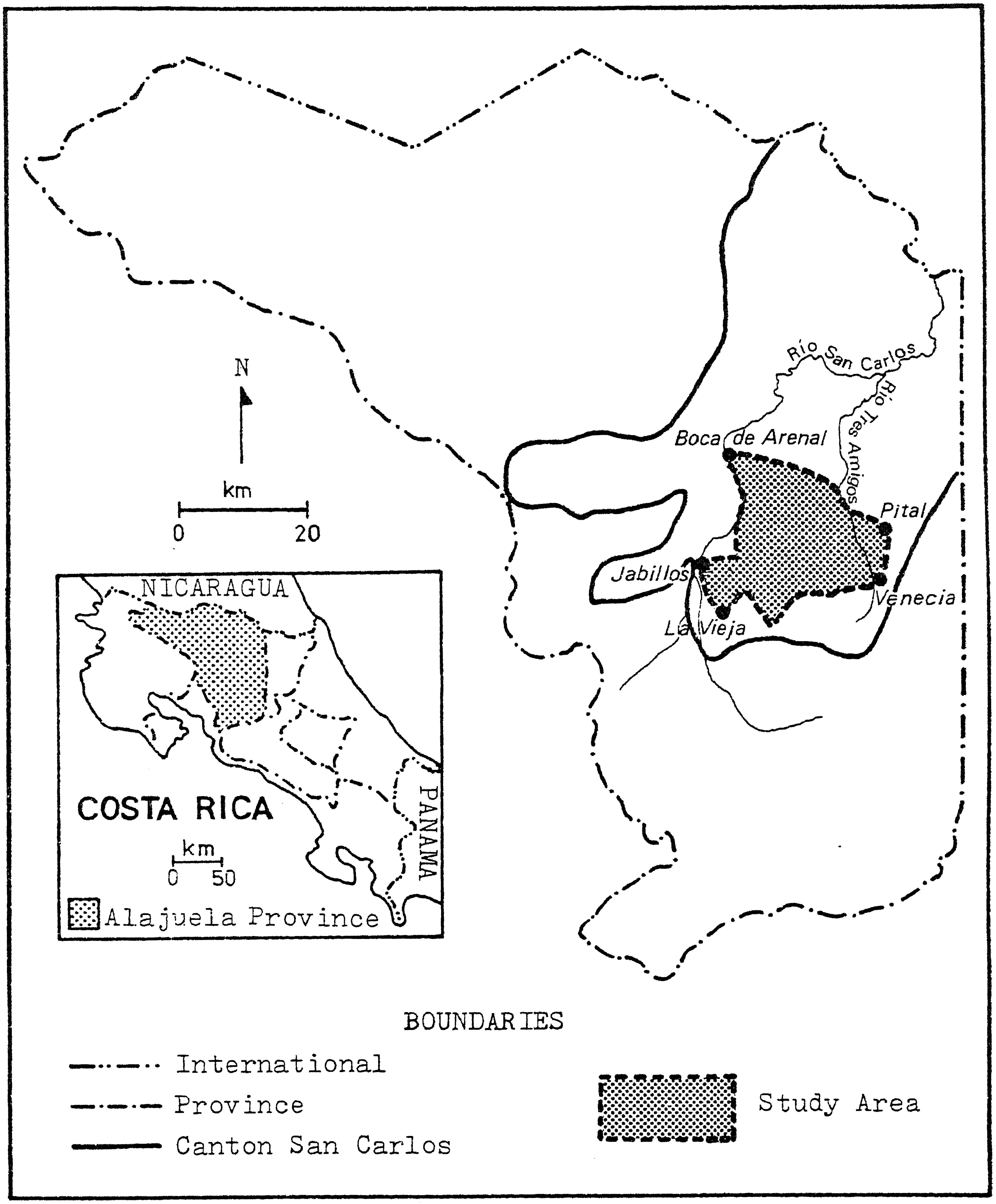


Fig. 1.--Location of study area.

of the Canton of San Carlos, in the south; a southeast-northwest line, extending between the villages of La Vieja and Jabillos, and the channel of the Río San Carlos, in the west; a northwest-southeast line, extending between the villages of Boca de Arenal and Pital, in the north.

Geology of Study Area

The geologic substrata in southern San Carlos are composed of alluvial, laharic (volcanic debris flow and mudflow), pyroclastic, and igneous deposits of predominantly andesitic composition and proposed Quaternary age (Malavassi V., 1966a, 1966b; Ministerio de Industria y Comercio, 1968). Stratigraphic studies, which were conducted to obtain more detailed information about the geology of the study area, were hampered by deep and intense subaerial weathering and the disjunct spatial distribution of many of the deposits. General observations are reported below.

Spatial Distribution of Deposits

In the lowland part of southern San Carlos, outcropping deposits are exclusively of laharic and alluvial origin. In contrast, in the piedmont part of the study area pyroclastic deposits are widespread and solid igneous extrusions are present at some localities. Volcanic ash mantles most of the higher, dissected terrain in the western and central parts and the entire terrain in the eastern part of this area. The thickness of pyroclastic surface units varies in response to local relief, being generally thicker on top of divides and on upper and lower slope segments than in mid-slope positions. Surface deposits on the lower, gently sloping terrain in the western and central parts of the piedmont area generally are of alluvial and laharic origin.

In areas where surface deposits consist of alluvium and laharic materials, shallow subsurface deposits generally also are of alluvial and laharic origin. Similarly, in areas where surface deposits are comprised of volcanic ash, immediately underlying subsurface deposits mainly are of pyroclastic and sometimes of laharic origin. Locally, stone lines, consisting of subangular to subrounded rock fragments of varying sizes, separate surface ash layers from underlying depositional units. Specific information about the nature and spatial distribution of deposits in different parts of the study area is provided in Chapter II and Appendix I.

Temporal Distribution of Deposits

Deposition was episodic in nature, resulting from intermittent volcanic activity and tectonic movements (AID Resource Inventory Center, Corps of Engineers, U.S. Army, 1965, p. T9; Weyl, 1961, p. 106), which in turn caused rapid mass flowages in the form of lahars and increased fluvial aggradation. Although all outcropping deposits in southern San Carlos have been assigned a Quaternary age, individual deposits were laid down at different times within this period.

A search for buried charcoal and wood, which was made in the hope that absolute ages of deposits could be determined, met with limited success because materials suitable for radiocarbon dating were found at only one locality. Moreover, uncorrected radiocarbon ages of three wood samples from this site, given as $38,615 \pm {}^{3,195}_{2,280}$ (Hv 3777), >43,000 (Hv 3778), and $40,740 \pm {}^{3,990}_{2,650}$ (Hv 3779) years before 1950 (Laboratorium des Niedersächsischen Landesamtes für Bodenkunde, Hannover, West Germany), most likely are greater than 40,000 years because of possible contamination of two of the samples (Geyh, 1971, written communication). Information about relative ages of deposits, based upon variations in degree of soil development, is provided in Chapters III and IV.

Climate of Study Area

The climatic regime of southern San Carlos is determined largely by the low-latitude geographic location of the area and its position on the Atlantic side of the fluvial divide of Central America. According to the Köppen classification system of climate, the entire area experiences a humid tropical (Af) climate. As is typical for such climates, mean monthly temperatures are above 18°C, variations in mean monthly temperatures are small compared to diurnal temperature variations, and annual precipitation totals are high. Regional variations in temperature and precipitation result mainly from differences in elevation. The following discussions of the precipitation and temperature regimes in southern San Carlos are based on climatic data recorded at two existing meteorological stations: Los Llanos (10°29'N, 84°23'W), located at an elevation of 180 m (meters) in the lowland part of the area; and Ciudad Quesada (10°17'N, 84°26'W), located at an elevation of 656 m in the piedmont part of the area (Ministerio de Agricultura y Ganadería, 1970).

Precipitation Regime

The precipitation regime of southern San Carlos, as that of other regions in Central America facing the Carribean Sea, is greatly influenced by the seasonal migration of the North Atlantic Anticyclone. A southward displacement of this high pressure cell during winter months results in frequent invasions of moisture-laden, northerly winds (Nortes), which produce persistent (orographic) precipitation on the windward sides of mountains. A northward and westward displacement of the North Atlantic high pressure cell during summer months causes an extension and intensification of the tropical Easterlies, resulting in convectional type of precipitation in the form of showers and thunderstorms in association with the passage of Easterly Waves. The winter and summer rainy seasons are interrupted by a drier season of varying duration in the spring. Sudden, short dry spells (Caniculas) may occur during mid-summer or late-summer months (Hastenrath, 1967b, 1968).

Mean annual precipitation for the period 1960-1969 was 456 cm (centimeters) at Ciudad Quesada and 330 cm at Los Llanos (Ministerio de Agricultura y Ganadería, 1970, p. 26, 59). Although rainfall is high throughout the study area, precipitation increases with altitude. The piedmont station, Ciudad Quesada, located within the local altitudinal belt of maximum precipitation (Hastenrath, 1967b, p. 233-237), clearly receives higher amounts of precipitation than the lowland station, Los Llanos (Fig. 2).

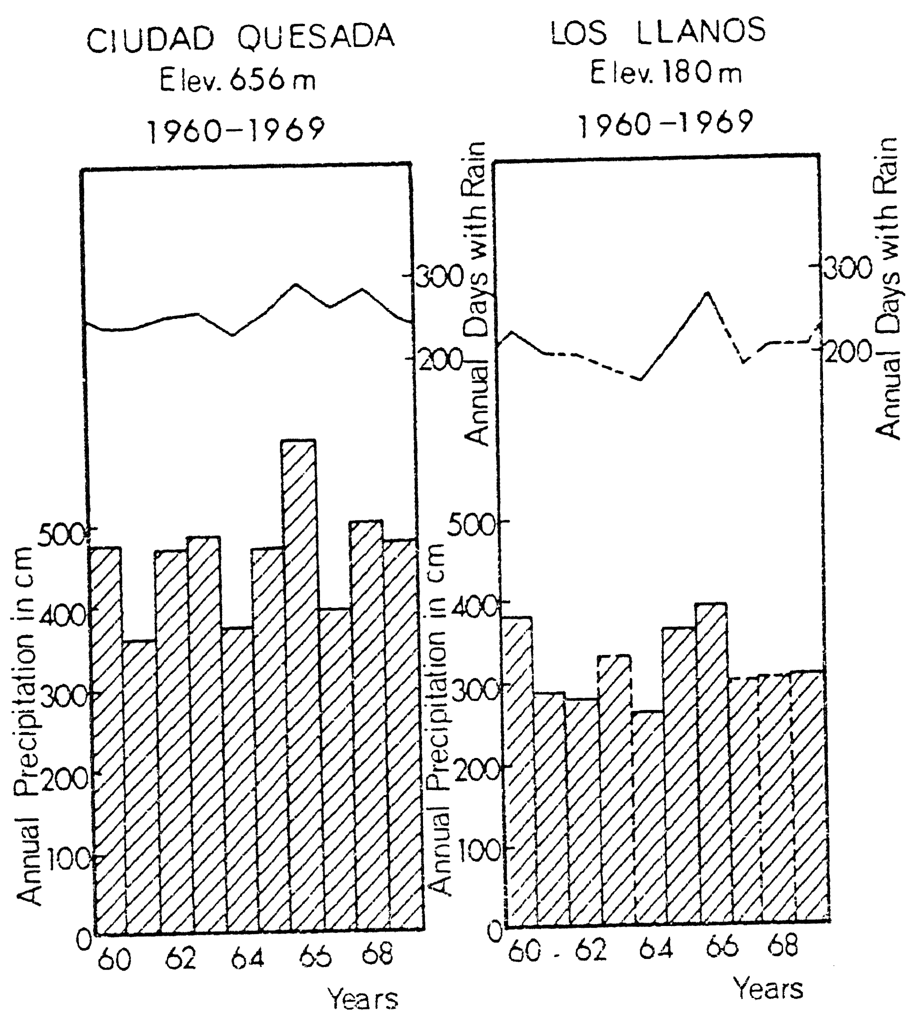


Fig. 2.--Total annual precipitation and annual days with rain recorded at Ciudad Quesada and Los Llanos during the period 1960-1969 (Source: Ministerio de Agricultura y Ganadería, 1970, p. 26, 27, 59, 60).

On the other hand, variations in annual precipitation are recorded at both stations. For example, during 1966, a particularly wet year, about one and a half times as much rain was received at the two stations than during 1964, a particularly dry year (Table 1).

TABLE 1.--Total Annual Precipitation in cm for Los Llanos and Ciudad Quesada for 1964, a Particularly Dry Year, and for 1966, a Particularly Wet Year

Year	Stations	
	Ciudad Quesada	Los Llanos
1964	372	260
1966	604	395

Source: Ministerio de Agricultura y Ganadería, 1970, p. 26, 59.

Variations in annual precipitation are caused by variations in large-scale atmospheric circulation patterns. During wet years, the winter circulation pattern is stronger and more persistent than during normal years, resulting in larger amounts of precipitation during the winter rainy season and a near-elimination of the spring dry season. During dry years, the winter circulation pattern is weaker and the summer circulation pattern starts later than during normal years, resulting in less precipitation during the winter rainy season and a longer, more pronounced spring dry season. For example, in 1966 abundant precipitation was received until February, and during the driest month of the wet spring of this year more rain fell than during the wettest month of the 1964 spring dry season (Fig. 3).

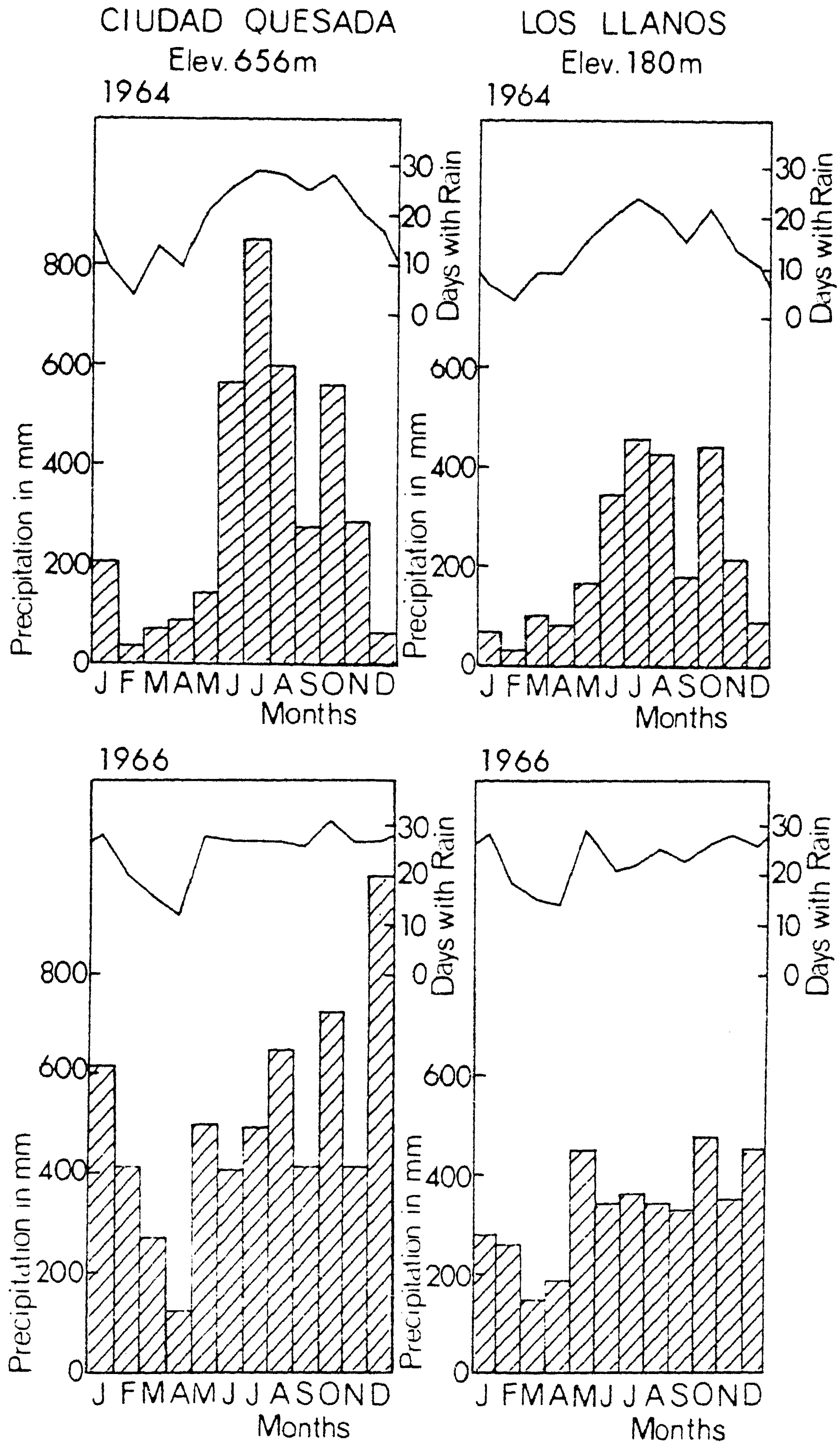


Fig. 3.--Total monthly precipitation and number of monthly days with rain recorded at Ciudad Quesada and Los Llanos during 1964, a particularly dry year, and during 1966, a particularly wet year (Source: Ministerio de Agricultura y Ganadería, 1970, p. 26, 27, 59, 60).

In 1964, the spring dry season started as early as December and lasted until May, the onset of the summer rainy season having been delayed until June. Although a decrease in precipitation was noticeable at the end of the summer rainy season in both 1964 and 1966, the late-summer dry spell was much more pronounced in the dry than in the wet year, as indicated by the smaller amount of precipitation recorded for September in 1964.

Variations in total number of annual days with rain correspond to variations in annual precipitation totals. Although the number of annual days with rain generally is high, the wetter piedmont part experiences rain on more days than the drier lowland part of the study area (Fig. 2). Moreover, the difference between the total number of annual days with rain in the two areas is greater during relatively dry than during relatively wet years (Fig. 3). For example, during the period 1960-1969 the piedmont station at Ciudad Quesada experienced an average of 39 more rainy days than the lowland station at Los Llanos. In the dry year of 1964, Ciudad Quesada received rain on 64 more days than Los Llanos, whereas in the wet year of 1966, the piedmont station reported only 21 more rainy days than the lowland station (Table 2).

TABLE 2.--Total Number of Annual Days with Rain for 1964 and 1966, and Mean Number of Annual Days with Rain for the Period 1960-1969 at Ciudad Quesada and Los Llanos

Year	Stations		Difference Between Stations
	Ciudad Quesada	Los Llanos	
1964	233	169	64
1966	296	275	21
Mean 1960-1969	262	223	39

Source: Ministerio de Agricultura y Ganadería, 1970, p. 27, 60.

Temperature Regime

Although there exists a decrease in temperature with increase in altitude, most of the study area lies in the tierra caliente, as defined by Sapper (1932, p. 12) who uses a mean annual temperature of 23°C to designate the upper limit of this zone. For the period 1960-1965, mean annual temperatures ranged from 27.0°C at the lowland station, Los Llanos, to 22.8°C at the piedmont station, Ciudad Quesada. At both stations, mean monthly temperatures were lowest at the end of the winter rainy season and highest at the beginning and/or end of the summer rainy season (Table 3). On the other hand, the total range in mean monthly temperatures for the six-year period amounted only to 1.5°C at Ciudad Quesada and 2.6°C at Los Llanos.

Compared to variations in mean monthly temperatures, diurnal temperature variations are large throughout the region. In general, they are smaller during wetter than

TABLE 3.--Mean Annual, and Highest and Lowest Mean Monthly Temperatures for the Period 1960-1965 at Ciudad Quesada and Los Llanos

Temperature (°C)	Stations	
	Ciudad Quesada	Los Llanos
Mean Annual	22.8	27.0
Highest Mean Monthly	23.5 (May, June, Sept., Oct.)	28.1 (Sept.)
Lowest Mean Monthly	22.0 (Jan.)	25.5 (Jan.)

Source: Nuhn, 1966, p. 34

during drier periods of the year and at higher than at lower elevations. During the period 1960-1965, diurnal temperature variations, as approximated from mean monthly maximum and minimum temperatures, ranged from 10.9°C to 14.5°C at the end of the winter and summer rainy seasons, respectively, at the lowland station, Los Llanos; and from 8.4°C to 10.8°C at the beginning of the summer rainy and spring dry seasons, respectively, at the piedmont station, Ciudad Quesada (Nuhn, 1966, p. 34). Although these data indicate that diurnal temperature variations decrease with altitude, as observed in other parts of the humid tropics (Troll, 1959, p. 23-24), they remain substantially greater than mean monthly temperature variations.

Pleistocene Climate

Pleistocene climate in southern San Carlos differed from Holocene climate mostly during glacial ages which were somewhat cooler and possibly moister, but not drier, than at present. For Costa Rica, a Pleistocene snowline depression of 800 m, determined by the altitudinal difference between a Pleistocene snowline of 3,500 m and an estimated Modern snowline of 4,300 m on Chirripó, the highest peak of the Cordillera de Talamanca (Hastenrath, 1963, p. 80, 82; 1967a, p. 547; 1971, p. 55, 61; Weyl, 1956a, p. 322-323; 1956b, p. 293), suggests a Pleistocene glacial-age temperature depression of 4.8°C in agreement with Pleistocene glacial-age temperature depressions determined by the snowline-depression method elsewhere in the humid tropics (e.g. Flohn, 1952, p. 170; Wilhelmy, 1957, p. 303, 307). However, in the light of most recent findings, this value appears to have been lower since during the height of the last glacial phase of the Wisconsin glaciation, summer surface temperatures of the adjacent part of the Pacific Ocean did not differ from those of today and summer surface temperatures of the Carribean Sea decreased by only 0.6°C (Gates, 1976, p. 1139; CLIMAP project members, 1976, p. 1132). Over land areas, the decrease in summer surface air temperatures apparently was greater, an estimated 3°C in Costa Rica (Gates, 1976, p. 1142). Using this value and mean summer temperatures (June through September) recorded at the two meteorological stations in the study area, glacial-age mean summer temperatures in southern San Carlos can be estimated. During the period 1960-1965, mean summer temperatures were 27.8°C at the lowland station, Los Llanos, and 23.3°C at the piedmont station, Ciudad Quesada (Nuhn, 1966, p. 34). Glacial-age mean summer temperatures of 24.8°C at Los Llanos and 20.3°C at Ciudad Quesada would have been only slightly lower than lowest mean monthly temperatures recorded at the two stations today (Table 3).

The Pleistocene glacial-age moisture regime in southern San Carlos appears to have been as much as or greater than that of today. A moisture regime similar to that at present would have been experienced if, as some authors believe (e.g. Flint, 1971, p. 417; Flohn, 1953, p. 272; Galloway, 1965, p. 77), lower amounts of precipitation were received due to reduced evaporation from the cooler equatorial regions of the Atlantic and Pacific Oceans (CLIMAP project members, 1976, p. 1136), since less rainfall would have been offset by a smaller evapotranspirative loss of moisture as a result of lowered temperatures. If precipitation amounts were similar to those at present, effective moisture in southern San Carlos would have been slightly greater during Pleistocene glacial ages than today, since less moisture would have been lost by evapotranspiration due to lowered temperatures. On the other hand, if rainfall was greater and more evenly distributed than today, due to increased cyclogenesis at the Intertropical Convergence Zone as a result of frequent invasions of polar air as other authors believe (e.g. Flohn, 1952, p. 161-162; 1953, p. 267-268; Willett, 1950, p. 180-181; Willett and Sanders, 1959, p. 190-192), the Pleistocene glacial-age moisture regime in southern San Carlos would have been substantially greater than at present. In summary, although the degree of available moisture in southern San Carlos during Pleistocene glacial ages cannot be determined with certainty, it should be noted that the climate of the area was certainly not drier, but equally as wet as, or perhaps wetter than, today.

Vegetation of Study Area

According to the Holdridge classification system of vegetation (Tosi, 1964, p. 173-181), the Modern natural vegetation in southern San Carlos falls into three major and three transitional vegetation zones. The former include tropical moist forest, tropical wet forest, and subtropical rainforest; the latter include a transition zone between tropical moist and tropical wet forest, a transition zone between tropical moist or wet and subtropical wet forest, and a transition zone between tropical wet forest and subtropical rainforest (Pérez and Chacón A., 1966, p. 88-112; Pérez, 1966). In general, as elevation increases from the lowland through the piedmont part of southern San Carlos, the tropical forest types, including the transition zone between tropical moist and wet forest, are succeeded by the transition zones between tropical and subtropical forest types, which in turn are followed by subtropical rainforest. However, it should be noted that the tropical forest types are most extensive, occurring throughout the lowland part and adjacent portions of the piedmont part of the study area, in contrast to subtropical rainforest, which is restricted to a relatively small area in the southcentral part of the piedmont.

During Pleistocene glacial ages, subtropical rainforest probably expanded downward in elevation, mainly at the expense of transitional forest zones, and covered a larger portion of the piedmont part of southern San Carlos. In contrast, the Pleistocene glacial-age natural vegetation in the lowland part of the study area most likely was similar to that of today because temperatures remained sufficiently high to support tropical forest types.

There also is supporting biogeographic evidence from outside the study area, provided by the vegetation of the higher mountains in Costa Rica, that offers some insight as to the magnitude of vegetational change in the lowland part of southern San Carlos during the glacials of the Pleistocene. Above the montane subtropical rainforest belt, there are extensive "temperate" forests of evergreen live oaks. However, pines or other boreal conifers are unknown now and in the past. The absence of pines in Costa Rica, Panama, and all of South America stands in contrast to the consistent presence of pine forests in the mountains of Central America from southern Mexico to Nicaragua. There is an obvious geographic obstacle to southward migration of high-montane plants at Lake Managua, Nicaragua, where an extensive tropical lowland constitutes a major break in the mountainous continental divide or cordilleran system of Central America. Several wide ranging species of pines and oaks reach the mountains of Nicaragua north of this lowland barrier. A gradient of drastically decreasing species richness of both pines and oaks from Mexico south to Nicaragua suggests that the migration has been from north to south. The live oaks of Costa Rica consist mainly of unique, endemic species, evolved in isolation on disjunct montane "islands". The geographic isolation for temperate-montane plants imposed by the tropical lowland of the Managuan break must not have been relieved by Pleistocene cooling. Therefore, the lowland climate of Central America, including that of southern San Carlos, has remained essentially tropical throughout the Pleistocene (P. V. Wells, personal communication, 1979). In summary, the available evidence indicates that Pleistocene glacial-age vegetational changes in southern San Carlos have been even less pronounced than past climatic changes in the area.

General Effects of Climate and Vegetation on Geomorphic and Pedogenic Processes in Study Area

Despite spatial and temporal variations in precipitation and temperature which are evident in southern San Carlos now, and which existed in the area during the past, both Holocene and Pleistocene climates have promoted the rapid alteration of landforms by geomorphic and pedogenic processes. This is true because the climate of the area as a whole has always been one that induces high intensity and continuous action of these processes, especially when compared to climates in other geographic regions. Rainfall has never been a limiting factor since current and past precipitation amounts have always been sufficiently high throughout the year to permit landform alteration to proceed at an undiminished rate. Present temperatures, although decreasing with altitude, are sufficiently high throughout the area to allow geomorphic and pedogenic processes to act upon landforms with similar intensity; past temperatures, although somewhat lower than today, did not drop low enough to greatly reduce the intensity of these processes.

Two main effects of current and past types of natural vegetation have been: (1) to create a microclimatic environment in which already small macroclimatic variations in temperature and precipitation were further dampened, allowing weathering and soil formation to proceed at relatively constant and uniform rates; and (2) to protect the surfaces of landforms from excessive erosion by reducing the impact of rain through interception and dispersion of the falling precipitation. Only since the latter part of the Nineteenth Century, when cultural vegetation and human structures started to replace the natural vegetation in southern San Carlos, have these effects been reduced.

In summary, new landforms which were created in southern San Carlos during episodes of landscape instability were readily altered by geomorphic and pedogenic processes during succeeding episodes of relative landscape stability because of the climatic and vegetational conditions prevailing in the area. As a result, landform boundaries tended to become obscured and differences with respect to soils tended to become subdued. Despite this tendency toward landscape homogenization, evolutionary trends in landscape formation could be established because episodes of landscape instability were spaced sufficiently in time so that landform surfaces acquired and retained diagnostic geomorphic and pedogenic properties.

CHAPTER II

GEOMORPHIC EVIDENCE

Introduction

In this chapter, principal landform types in southern San Carlos are described, the origin and spatial distribution of landforms are discussed, and information about relative ages of landforms which can be obtained from their spatial distribution is given. Following a brief description of methods, major landform types in the Atlantic Lowland and Piedmont Provinces of the study area are treated. The chapter concludes with a discussion of spatial and temporal relationships between major landform types in southern San Carlos.

Methods

Interpretations of landforms were made from field observations, topographic maps, and aerial photographs. Topgraphic maps at a scale of 1:50,000 and vertical black-and-white aerial photographs at a scale of 1:60,000 were available from the Instituto Geográfico Nacional (National Geographic Institute) of Costa Rica, a bureau under the Ministry of Transportation. In addition, low-altitude oblique black-and-white and color aerial photographs were obtained from a light aircraft in the spring of 1970. The topgraphic maps and the high-altitude photographic imagery both were very useful for the recognition of regional relationships between landforms. The low-altitude photographs facilitated the documentation of low-relief geomorphic features, which are not distinguishable on the topographic maps nor detectable on the relatively small-scale vertical aerial photographs.

Most of the study area is covered on the Aguas Zarcas topographic sheet (Instituto Geográfico Nacional, 1967). Other topographic sheets which were used in the present study include: Quesada, Tres Amigos, Fortuna, Río Cuarto, and San Lorenzo [Instituto Geográfico Nacional, 1966a-e (Fig. 4)]. Copies of the Aguas Zarcas and Quesada topographic sheets, which are most relevant to the present study, are included for reference (Appendix IV).

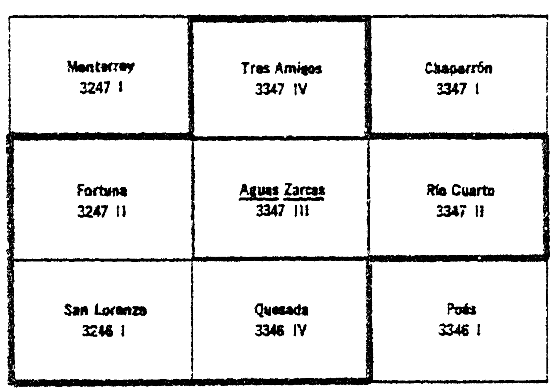


Fig. 4.--Index map of topographic sheets. The sheets which were used in the present study are enclosed by a heavy black line. The study area is centered on the Aguas Zarcas sheet.

Although field work for the present study was initiated during the summer of 1968, detailed observations with respect to landforms were made mainly during a two-month period in the spring of 1970. They included: (1) stratigraphic studies of numerous sections exposed in roadcuts, stream banks, and quarries; (2) determinations of pebble and boulder lithologies; (3) measurements of boulder orientations on alluvial/laharic fans (with Brunton compass); (4) measurements of landform slopes (with Brunton compass); (5) measurements of landform heights (with Abney level); and (6) mapping of landform boundaries on topographic maps. Detailed notes of field observations were kept throughout the study, often documented by sketches and photographs.

Landforms in the Atlantic Lowland Province of Southern San Carlos

The northern part of the study area, referred to as the Atlantic Lowland Province of southern San Carlos, is located in the southcentral, most accessible part of the Atlantic Lowland Province of the Canton of San Carlos (Fig. 5). The triangular boundaries of this part of the study area are approximately defined by: the distal end of an alluvial/laharic fan and the base of a northeast-southwest running escarpment, in the south; the channel of the Río San Carlos, in the west; and a northwest-southeast line, extending from the settlement of Boca de Arenal to the Río Tres Amigos, in the north (Figs. 1 and 5).

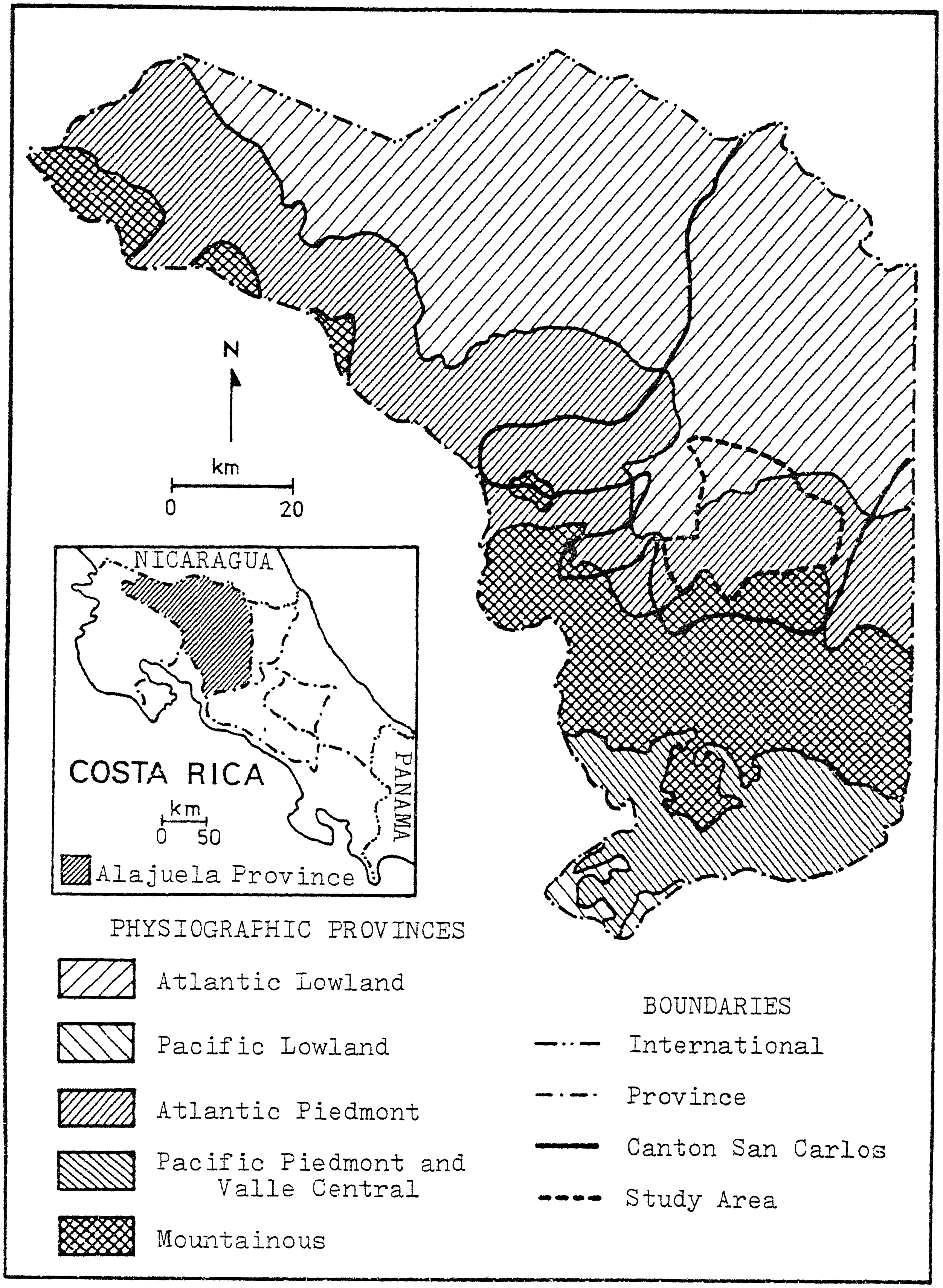


Fig. 5.--General extent of major physiographic regions in the Province of Alajuela, the Canton of San Carlos, and the study area (Modified and expanded from Sandner, 1966a).

Elevations are relatively uniform throughout most of the Atlantic Lowland Province of southern San Carlos. Average elevations range from 70 m in the northern part to 80 m in the southern part of the area. Toward the perimeters, elevations become slightly higher or lower. In the north and northeast, elevations gradually increase from 70 m to 80 m, whereas in the southeast they gradually increase from 80 m to 100 m. Toward the southcentral, southwestern, and western boundaries of the area, elevations change within relatively short horizontal distances. In the south, elevations increase from 80 m to 100 m, whereas in the west elevations drop to as low as 50 m along the channel of the Río San Carlos.

In the literature, the Atlantic Lowland Province of southern San Carlos has been described as an undulating plain of low relative relief with small hills and terraces along major streams (Sandner, 1966a, p. 19-20; 1966b). Deposits making up these landforms were originally designated as Pleistocene alluvium with two isolated occurrences of Quaternary volcanics in the western part of the area (AID Resource Inventory Center, Corps of Engineers, U.S. Army, 1965, two maps on the geology and rock types of Costa Rica, no page numbers). Later, deposits were reinterpreted as being fine-textured laharic materials of Quaternary age with narrow zones of Quaternary alluvium along major streams (Malavassi V., 1966b; Ministerio de Industria y Comercio, 1968). In the present study, previous work is reevaluated and expanded. In particular, three major landform types are discussed: (1) small hills of laharic origin; (2) alluvial plains; and (3) stream terraces.

Small Hills of Laharic Origin

Small hills which rise above the generally flat terrain of the Atlantic Lowland Province of southern San Carlos are present at many localities throughout the area. They were studied most intensively near the villages of Muelle San Carlos and Boca de Arenal, in the west; along the Río Kopper in the vicinities of the Finca Alpízar Castro and the Sociedad Ganadería Río Kopper, in the central part of the area; and in the surroundings of the Hda. (Hacienda) Altamira, in the east (Figs. 6 and 7). A description of the characteristic features of these hills is in order.

(1) Most hills are oval in shape and have flat tops. On the other hand, some of the smaller hills are perfectly conical in shape and have rounded tops.

(2) The height of hills ranges from 5 to 20 m, although at given localities hills tend to rise to similar elevations.

(3) The spacing of hills is irregular. At some sites individual hills are located in close proximity, whereas at others they may be separated by more than 100 m.

(4) The orientation of hills varies but, where occurring in groups, hills tend to trend in similar directions. For example, in the vicinity of the Hda. Altamira groups of hills and individual hills are oriented north-south;

Fig. 6.--Oblique aerial view of the surroundings of the Hda. Altamira. Note the small hills of varying shapes and sizes which are present throughout the area.

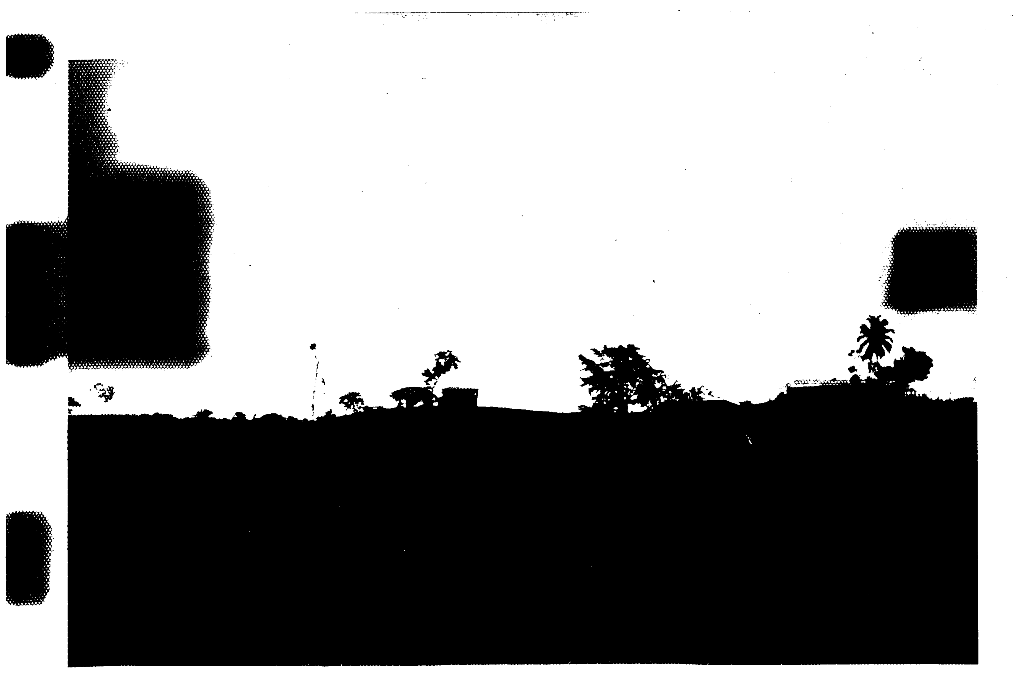


Fig. 7.--Ground view of two closely spaced, oval hills at the Sociedad Ganadería Río Kopper. Note the similar heights of the hills and the distinct break in slope at the bases of hills, best seen in the left center.

in the surroundings of the Sociedad Ganadería Río Kopper, most hills are elongated in a northeast-southwest direction. In other areas, no persistent orientation of hills is recognizable.

(5) A rather abrupt break in slope exists between the bases of most hills and surrounding lower landform surfaces. For this reason, it was postulated that hills are partially buried and not exposed in their entirety. Verification of this hypothesis was prevented by unsuccessful coring attempts due to equipment failure.

Origin of Small Hills

Available field evidence and study of topographic maps and aerial photographs support the most recently proposed laharic origin of small hills in the Atlantic Lowland Province of southern San Carlos. The location of hills on gently sloping, undulating terrain beyond the margins of several large volcanoes, the ubiquitous distribution of hills over an extensive area, and the observed variations in the size, shape, and spacing of hills are characteristic of small mounds on the hummocky surfaces of massive lahars. On the other hand, bouldery cores typical of such mounds were recognized only in the western part of the Atlantic Lowland Province, possibly because of a general lack of large vertical exposures (greater than 5 m) in the remainder of the area. Information about the original texture of deposits composing the small hills could not be obtained because of intense and deep subaerial weathering.

Possible source areas for lahars sufficiently large in size to have created the small hills in the Atlantic Lowland Province of southern San Carlos are the summit areas and upper slopes of Volcán Viejo and Cerro Porvenir, two large strato-volcanoes, located south of the study area in the Mountainous Province of San Carlos. Both volcanoes have experienced large-scale destruction of their summit area, possibly as a result of tectonic movements or the collapse of crater walls during volcanic eruptions, events which reportedly have caused the formation and subsequent descent of massive lahars beyond the foot of volcanoes in other geographic regions (e.g. Crandell, 1971, p. 9). Massive lahars may also have been triggered during the formation of an immense fault scarp (Fila La Chocosuela) which extends northward from the summit area of Volcán Viejo, rising to as much as 700 m above the adjacent channel of the Río Aguas Zarcas (Quesada topographic sheet in Appendix IV).

The argument for a laharic origin of the small hills in the Atlantic Lowland Province of southern San Carlos is strengthened by the fact that several other possible modes of origin, including dissected, former alluvial plains, isolated cinder cones, and minor topographic features on the surfaces of lava flows, can be ruled out.

(1) If the small hills were remnants of dissected, former alluvial plains, they would be broader and more continuous because of the relatively coarse drainage pattern

in the area. Even frequent shifting of stream courses would not have been able to create the oval and sometimes perfectly conical shapes of hills.

(2) The hills are too ubiquitous, too small, and generally located too close together to be individual cinder cones. Several cinder cones which are present in the Piedmont Province of southern San Carlos differ from small hills in the Atlantic Lowland Province of the study area in a number of ways: the cinder cones are much fewer in number; half and possibly more of them are structurally controlled; they attain much greater heights; and they always are isolated features which are separated by several hundred to several thousand meters.

(3) Although in areas where small hills are closely spaced the topography resembles that of weathered lava flows with tumuli, squeeze-ups, and pressure ridges, closer investigation eliminated this mode of origin. A first hand look at an area of recent basalt flows, which extends southeast of the study area (Fig. 8), immediately revealed several differences: the small hills in the Atlantic Lowland Province of southern San Carlos are more varied in size and shape, seldom as markedly aligned, more irregular spaced, and more widespread than those present in the basalt-flow area.

There also is a lack of nearby volcanic centers from which extensive lava flows might have originated. Cerro Platanar, the nearest large volcano, is located aproximately

Fig. 8.--Basalt-flow topography with small, nearly conical, closely spaced hills, which are aligned in the direction of flow, southeast of the study area.

20 km (kilometers) to the south and appears to be an unlikely source, especially since recent lava flows are restricted to the slopes of the volcano. Cerro Los Chiles, a smaller volcanic center, which is located approximately 5 km southeast of the southern limit of small hills in the eastern part of the Atlantic Lowland Province of southern San Carlos, is an equally unlikely lava source because it is composed mainly of pyroclastic materials. Small lava flows, which extruded on the eastern and northern flanks of the cinder cone, hardly extend beyond its base.

Alluvial Plains

Alluvial deposits are much more widespread in the Atlantic Lowland Province of southern San Carlos than most recently reported (Malavassi V., 1966b; Ministerio de Industria y Comercio, 1968). Alluvium occurs not only along present-day stream courses, but also in areas currently not traversed by streams, indicating that stream channels have shifted in the past. Alluvial deposits are most extensive in areas where small hills of laharic origin are located farther apart, whereas in areas in which the laharic landforms occur in close proximity alluvium tends to be absent.

The alluvium consists of numerous depositional layers of varying thickness, ranging from a few centimeters to several tens of centimeters. Upper depositional units are composed mainly of silt and sand and frequently are separated by pebbly stone lines. Lower depositional units often consist of medium or coarse gravel. The observed variations in both thickness and texture of individual depositional units suggest that fluvial aggradation has been episodic in nature and has varied in intensity. Moreover, the fact that intensely weathered small hills of laharic origin attain greater heights than surrounding, slightly weathered alluvial plains suggests that episodes of fluvial aggradation occurred more recently than laharic deposition.

Origin of Alluvial Deposits

Textural characteristics of sediments composing the alluvial plains in the Atlantic Lowland Province of southern San Carlos suggest that they were not acquired by streams locally, but were imported into the area from other portions of their drainage basins. Most major streams which traverse the lowland part of the study area and their larger tributaries originate in the Mountainous Province of San Carlos. Smaller tributary streams originate mainly in the Piedmont Province of the study area. A few, mostly very small tributaries originate in the Atlantic Lowland Province proper.

The described drainage characteristics point to the Mountainous Province of San Carlos as the principal source area for the alluvial deposits in the Atlantic Lowland Province of southern San Carlos. The materials which are being incorporated into the bedload of major streams in their upper reaches are relatively unweathered because they are acquired from formerly buried rock strata now exposed along the bed and sides of stream channels in deep valleys created by fluvial erosion. Relatively unweathered debris is also supplied by active mass wasting from adjacent steep valley walls. Tributary streams in the Mountainous Province of San Carlos attain slightly weathered materials from the surfaces of relatively recent lava flows.

A secondary source area for the alluvial deposits in the Atlantic Lowland Province of southern San Carlos is the Piedmont Province of the study area, where numerous small tributary streams originate on the surfaces of alluvial/laharic fans. The materials which enter the drainage systems from these landforms exhibit a relatively low degree of weathering similar to that of sediments derived from the Mountainous Province of San Carlos. Several small tributaries which originate on the higher, dissected terrain in the northcentral part of the Piedmont Province and the few small tributaries which originate in the Atlantic Lowland Province proper acquire more highly weathered sediments. However, these fine materials tend to be incorporated into the suspended load of streams and generally are being deposited outside the study area.

Stream Terraces

Flights of paired terraces, which rise above present-day stream channels, constitute the third major landform type in the Atlantic Lowland Province of southern San Carlos. The number of terraces varies along different streams. Two terrace levels are present along the Río Kopper; a total of four terrace levels are recognizable along the larger Río San Carlos (Figs. 9 and 10).

The presence of paired terraces suggests that episodes of fluvial aggradation, which built up alluvial plains in the Atlantic Lowland Province of southern San Carlos, were succeeded by episodes of fluvial degradation. The observed terrace characteristics imply that: (1) fluvial degradation periodically intensified, since paired terraces do not result from continuous, concomitant downcutting and lateral

Fig. 9.--Paired terraces along the Río Kopper at the Finca Alpízar Castro. The lower terraces are 2 m and the upper terraces 3 m above the present bed of the stream.

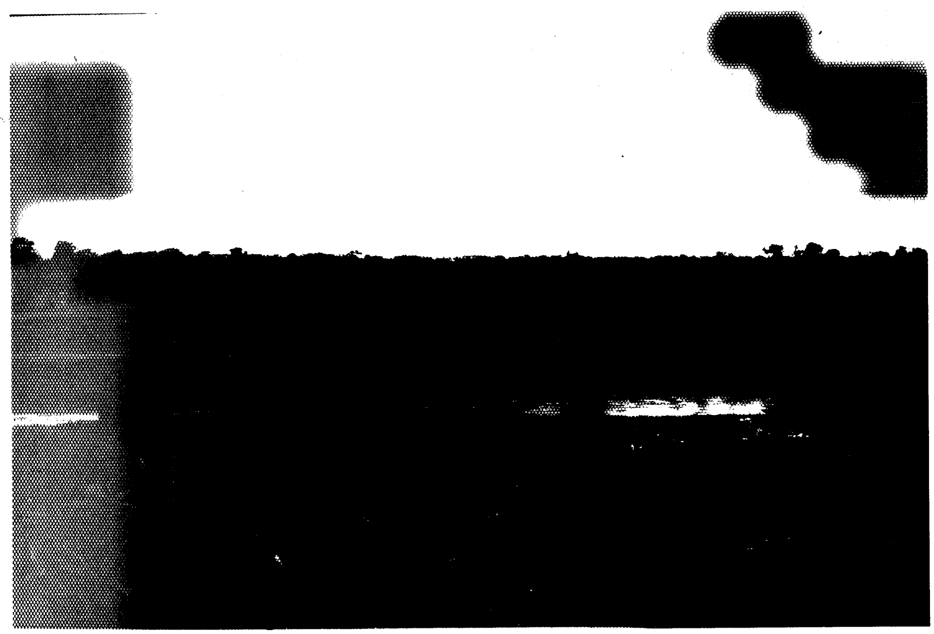


Fig. 10.--Flight of four terraces along the left bank of the Río San Carlos between the village of Boca de Arenal and the Finca Las Americas. Note that at present lower terraces are being partially destroyed by lateral stream erosion and slumping.

erosion of meandering stream channels; and (2) episodes of intensified fluvial degradation were relatively short-lived, as indicated by the small height of individual terraces and the proximity of terraces to present-day stream channels. At present, streams are most actively involved in lateral erosion, as evidenced by the destruction of terraces on the outside of meander bends (Fig. 10).

Origin of Stream Terraces

Causes for the formation of terraces along the Río San Carlos could not be determined because it was beyond the scope of the present study to investigate the large and diverse drainage basin of this stream, which covers hundreds of square kilometers west and north of the study area. Moreover, a systematic survey of terraces along the Río Kopper is required in order to ascertain which of two possible causes, discussed below, led to the formation of terraces along this stream.

Formation of terraces along the Río Kopper, which is part of the lower Río Aguas Zarcas drainage system (Fig. 20), may have resulted from successive channel adjustments of the Río Aguas Zarcas in response to stream derangement by the deposition of a massive lahar in the Piedmont Province of southern San Carlos. The presence of two terraces, occurring 5 m and 9.5 m, respectively, above the present bed of the Río Aguas Zarcas upstream from the area where this stream branches into several channels, including the Río Kopper, suggests two episodes of increased downward fluvial erosion. Despite differences in height, formation of these terraces and those present along the Río Kopper may be related, since the height of terraces tends to decrease downstream (Leopold et al., 1964, p. 475; Thornbury, 1969, p. 159). Moreover, the lower height of terraces along the Río Kopper, although being the largest of the lower Río Aguas Zarcas stream branches, may in part stem from a reduction in discharge, since it does not carry the entire discharge from the upper, undivided channel of this stream. Alternatively, formation of terraces along the Río Kopper may have occurred in response to episodic lowering of the local base level, caused by successive downcutting of the Río San Carlos. However, this mode of origin seems plausible only, if the greater number of terraces observed along the Río San Carlos resulted from hydrologic changes in the drainage basins of two of its large western tributaries, which enter the Río San Carlos downstream from its confluence with the Río Kopper.

Landforms in the Piedmont Province of Southern San Carlos

The southern part of the study area, referred to as the Piedmont Province of southern San Carlos, includes central and eastern portions of the Piedmont Province of the Canton of San Carlos (Fig. 5). The boundaries of this part of the study area are approximately defined by: a north-south line, extending between the villages of Pital and Venecia, in the east; irregular margins of lobate lava flows, in the south; a southeast-northwest line, extending between the villages of La Vieja and Jabillos, in the west; and the bases of two escarpments, the distal end of an alluvial/laharic fan, and a northwest-southeast line, extending from the Río Tres Amigos to the village of Pital, in the north (Figs. 1 and 5).

Due to the diverse nature of the terrain, elevations and slope angles both vary widely in the Piedmont Province of southern San Carlos. Elevations range from approximately 100 to 800 m. Slope angles range from less than 1° (degree) to almost 90°. Major landform types in the area include: (1) tilted fault-block ridges; (2) alluvial/laharic fans; (3) alluvial plains; and (4) cinder cones and associated pyroclastic deposits (Fig. 11).

Tilted Fault-Block Ridges

The most prominent topographic features in the Piedmont Province of southern San Carlos are three escarpments, which rise steplike above the Atlantic Lowland Province of the study area. They constitute the steep, northerly facing slopes of ridges, which trend southwest-northeast in the western part and northwest-southeast in the central part of the Piedmont Province (Fig. 11). The available evidence, which is discussed below, suggests that the escarpments are fault scarps, and that the ridges are tilted fault blocks.

Although the faults responsible for the formation of the three fault-block ridges are mostly concealed by mass-wasting debris or alluvial deposits, the following charac-

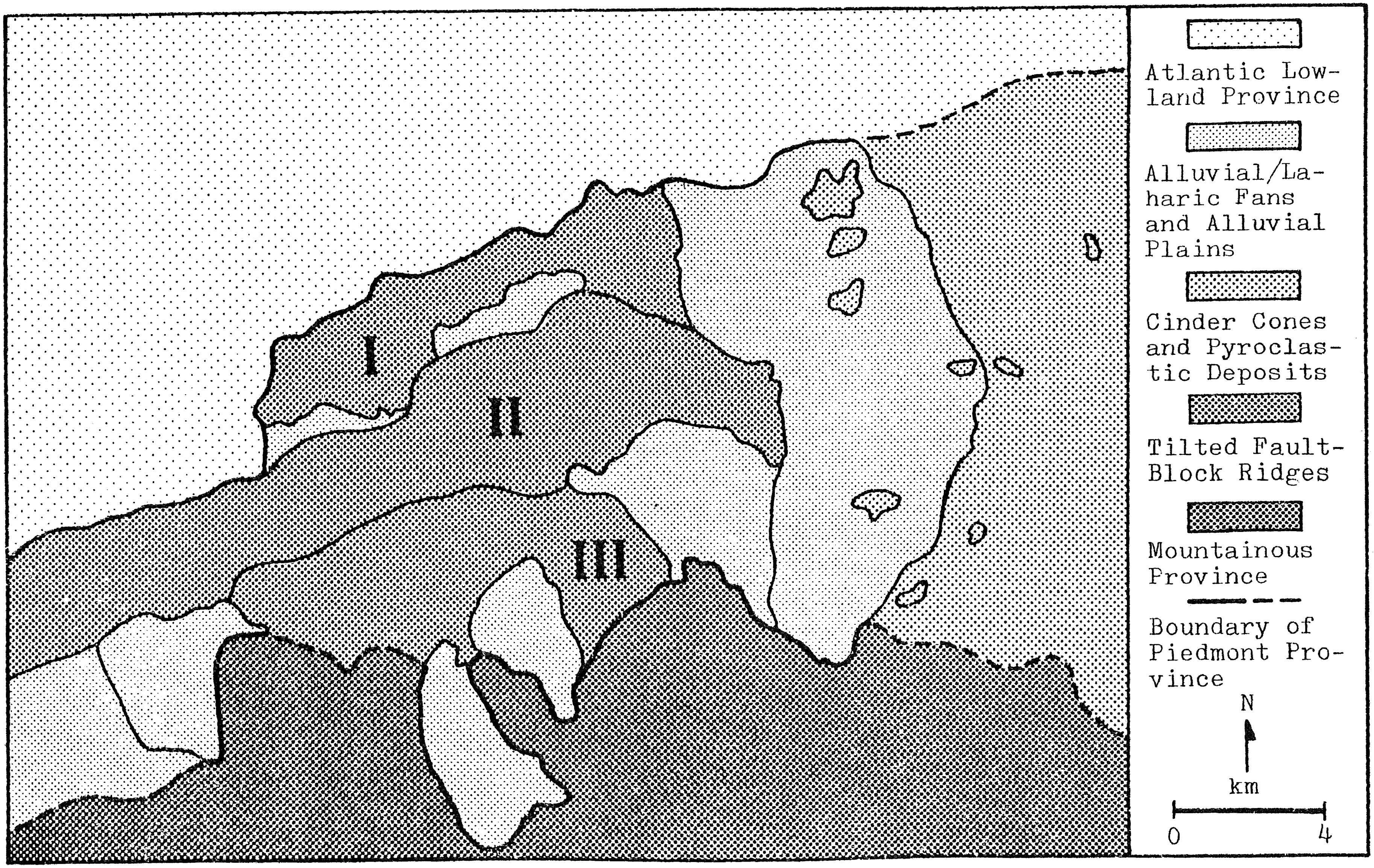


Fig. 11.--Major landform types in the Piedmont Province of southern San Carlos. East and west boundaries of the area are arbitrary north-south lines.

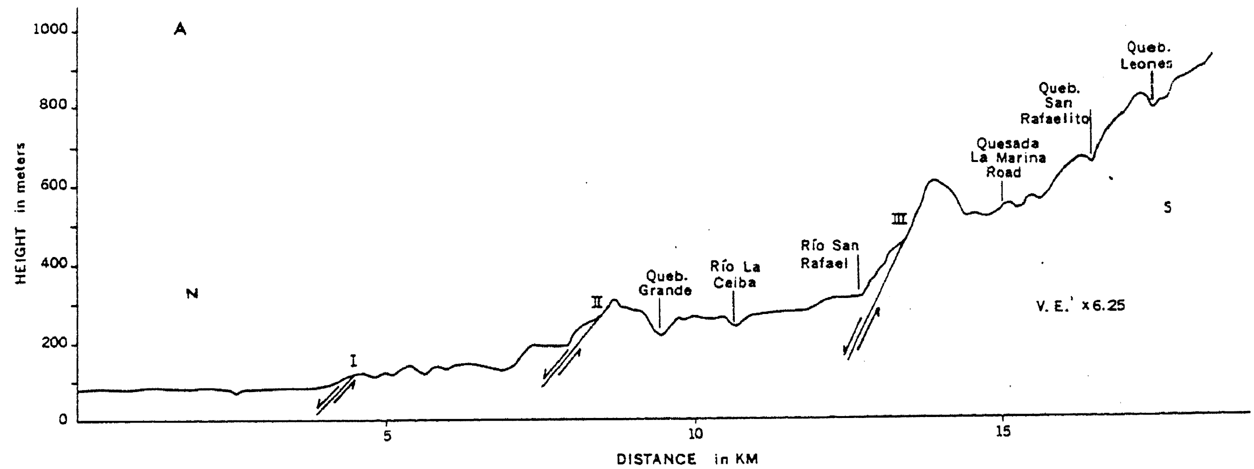
teristics of the fault system can be recognized.

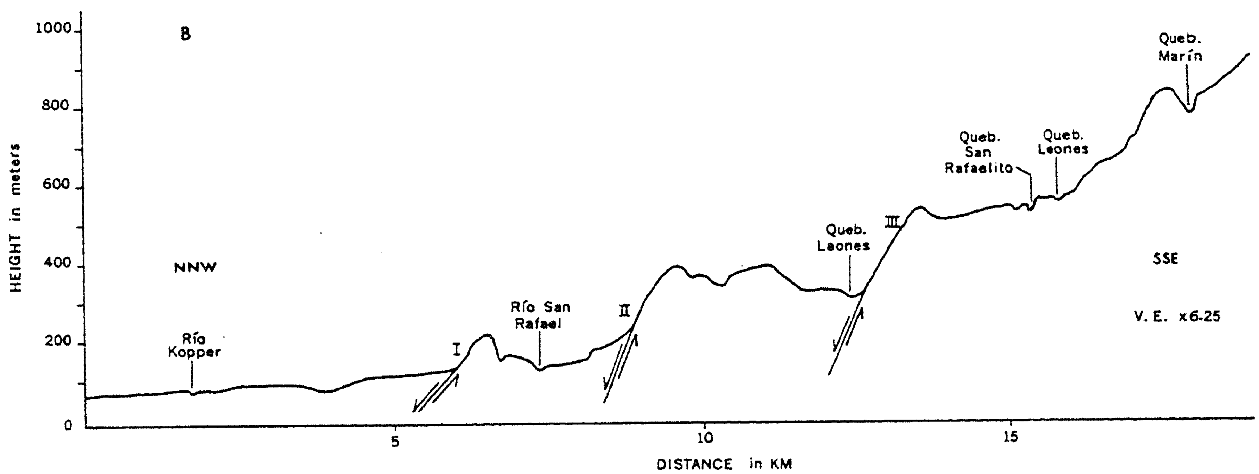
(1) When viewed over their entire lengths, the faults, rather than forming straight lines, are sinuous in plan, consisting of a series of individual, slightly offset segments that follow the general trend of the fault system. This is not unusual, since most faults that extend over appreciable distances seldom are perfectly straight (Thornbury, 1969, p. 242).

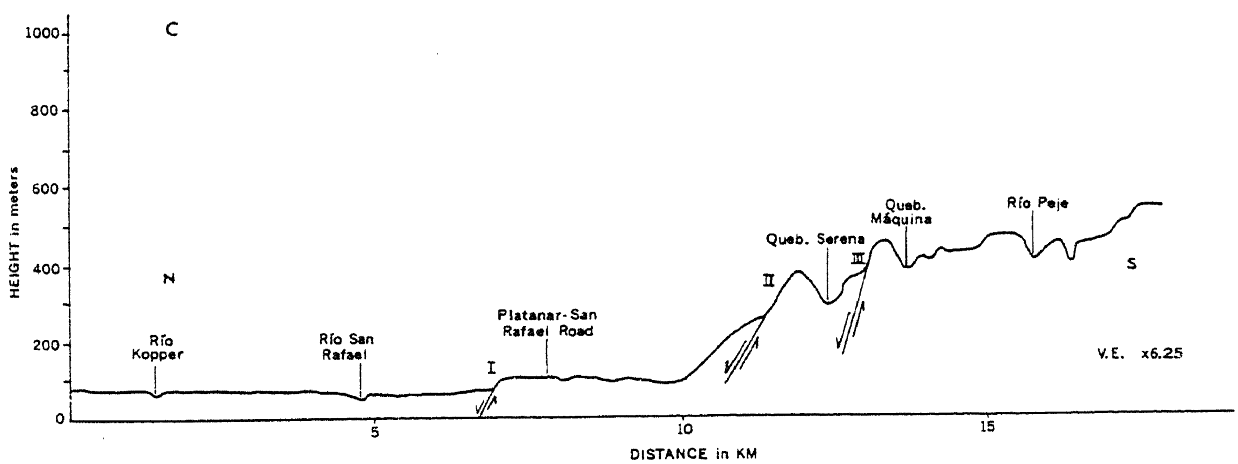
(2) The horizontal distance between faults I and II remains relatively constant over the entire length of the fault system. In contrast, the spacing between faults II and III increases markedly from west to east (Figs. 11 and 12). The greatest increase in horizontal distance between these two faults occurs in the central part of the fault system, where they change direction and turn toward the southeast. The distance which separates faults II and III in the east is about three times greater than in the west.

(3) Vertical displacements of rock strata along the three faults have varied, as indicated by differences in the overall height of associated fault scarps and variations in height along individual fault scarps (Fig. 12). Fault scarp I is the lowest among the three fault scarps. It ranges in height from 20 m toward its eastern and western ends to 80 m along its central portion. Fault scarps II and III attain comparable heights of 230 m and 250 m, respectively, along their central portions, but vary in height along their eastern and western portions. Toward

Fig. 12.--Topographic profiles constructed from the Aguas Zarcas topographic sheet (Appendix IV). Profile A, drawn along the 494,000^{m}E UTM (Universal Transverse Mercator) grid line, and Profile B, drawn between the 493,000^{m}E and 489,400^{m}E UTM grid lines, show the relief in the central part of the study area. Profile C, drawn along the 487,000^{m}E UTM grid line, shows the relief in the westcentral part of the study area. All three profiles are bounded by the 257,050^{m}N UTM grid line in the south and the 275,000^{m}N UTM grid line in the north. Profiles A and C are north-south profiles; Profile B extends northwest-southeast. The three fault scarps in the Piedmont Province of southern San Carlos are designated by the Roman numerals I, II, and III in each profile.


A
1000
800
600
400
200
0
HEIGHT in meters
N
S
I
II
III
Queb. Grande
Río La Ceiba
Río San Rafael
Quesada La Marina Road
Queb. San Rafaelito
Queb. Leones
V. E. x6.25
5
10
15
DISTANCE in KM


B
1000
800
600
400
200
0
HEIGHT in meters
NNW
SSE
I
II
III
Río Kopper
Río San Rafael
Queb. Leones
Queb. San Rafaelito
Queb. Leones
Queb. Marín
V. E. x6.25
5
10
15
DISTANCE in KM


C
1000
800
600
400
200
0
HEIGHT in meters
N
S
I
II
III
Río Kopper
Río San Rafael
Platanar-San Rafael Road
Queb. Serena
Queb. Máquina
Río Peje
V.E. x6.25
5
10
15
DISTANCE in KM

the east, fault scarp II decreases in height to as low as 160 m before increasing again in height to 260 m toward its eastern end; in contrast, fault scarp III consistently increases in height to as high as 360 m. Toward the west, fault scarp II gradually increases in height to 320 m along its westcentral portion before rather abruptly decreasing in height to between 80 and 90 m toward its western end; in contrast, fault scarp III gradually decreases in height to 180 m toward its western end.

(4) Faulting and uplift that created the fault-block ridges have been associated with tilting, as indicated by a southward dip of rock strata away from the crests of the ridges in opposition to the regional slope of the area. In comparison to the other two fault-block ridges, tilting of fault-block ridge I has been less pronounced. However, all three tilted fault-block ridges have steeper front scarps than backslopes (Fig. 12).

Evidence for Faulting and Uplift

Escarpments are common landforms and may not necessarily have been produced by faulting. However, in geologically unstable areas, escarpments, such as those displayed in the Piedmont Province of southern San Carlos, most likely have been created by tectonic movements.

Two types of scarps are common along faults: fault scarps, resulting directly from faulting; and fault-line scarps, produced by differential erosion along faults. Many of the features which are indicative of faulting occur along both types of scarps, including: an abrupt and imposing front; triangular facets on spur ends; a linear base to the scarp; sharp V-shaped canyons with bedrock floors extending down to the fault line; hanging valleys on the face of the scarp; springs along the base of the scarp; outflow of lava along the fault; frequent landsliding along the scarp; alignment of notches, cols, and jogs in ridges showing no lithologic control; long, straight, parallel stream courses across rocks of varying types and structures; and nearly right-angled offsetting of stream courses (Thornbury, 1969, p. 242-245). Most of these features, as discussed below in detail, are present along portions of the escarpments in the Piedmont Province of southern San Carlos. However, although providing evidence for a tectonic origin of the escarpments, they do not prove that the escarpments are fault scarps rather than fault-line scarps.

Positive or strongly presumptive evidence in support of fault scarps is provided by the following factors:

(1) Poor correlation between rock strength and topographic forms.--The escarpments have formed in relatively weak rocks, including unwelded, stratified volcanic tuffs, volcanic ash, laharic deposits, and alluvium. Thus, it is unlikely that they have been produced by erosional processes along faults. Moreover, although few portions of the faults are exposed, where not concealed, no appreciable differences in the composition and strength of rocks on opposing sides of the faults are recognizable. Such

differences would be a prerequisite for the formation of fault-line scarps.

(2) Tilting of ridges.--The ridges which rise above the faults show evidence of tilting, as indicated by a reversal of dip in rock strata composing their backslopes. Differential erosion along faults would have preserved the original dip of the rocks, which presumably were laid down conformably to the regional slope of the area. The fact that the escarpments form the front scarps of what appear to be tilted fault blocks suggests that they are fault scarps rather than fault-line scarps.

(3) Recency of faulting.--Although the escarpments are older than 40,000 years, as determined by three radiocarbon dates (p. 8), they are young in terms of geologic time. This suggests that they are fault scarps rather than fault-line scarps, since most escarpments of Quaternary age in tectonically active areas are believed to have been produced as a direct result of faulting (Thornbury, 1969, p. 246-247).

The above evidence implies that the escarpments in the Piedmont Province of southern San Carlos are fault scarps. Therefore, some of the features listed previously as being indicative of both fault scarps and fault-line scarps are discussed below in detail as supportive evidence for the existence of fault scarps.

Landslides

Landslides are common features along fault scarps because their steep slopes promote the formation of these landforms. Along the escarpments in the Piedmont Province of southern San Carlos landsliding has been extremely active, indeed so much so that the faults at the bases of the escarpments frequently are concealed. Alterations which have resulted from landslide activity along the eastern portion of fault scarp III are described as an example (Fig. 13).

The most drastic alteration along the eastern portion of fault scarp III has been caused by a massive landslide, which most likely was triggered by reactivation of the fault at the base of the escarpment. The crown of this slide coincides with the crest of the fault scarp and, where not altered further, the main scarp of the slide descends at a near 90° angle. The disturbed materials, forming the hummocky topography characteristic of the lower portions of landslides, cover an area of approximately one square kilometer and effectively conceal the fault at the base of the scarp.

Superimposed upon this massive landslide are numerous smaller landslides and slumps, which appear to have been triggered by mechanisms other than tectonic movements. For example, several landslides along the main scarp of the massive landslide probably resulted from oversteepened slopes. One fairly large landslide on the lower eastern

Fig. 13.--Landslide topography along the eastern portion of fault scarp III. A massive landslide of tectonic origin, which most drastically altered the appearance of the scarp, is seen in the center. In the center background, note the crown and steep main scarp of the slide along the forested upper portion of fault scarp III. The hummocky topography in the center middle ground represents the disturbed lower portion of the slide. Smaller landslides can be recognized along the main scarp of the massive lanslide and the upper portion of the fault scarp. Slumps are very conspicuous on the surface of the disturbed lower portion of the massive landslide. One large slump, which has occurred along the lower portion of fault scarp III, can be seen in the right center. One fairly large landslide, which was caused by undercutting of the Río San Rafael, is clearly visible to the south of the present stream channel on the lower left side of the massive landslide. In the foreground, a portion of the La Marina alluvial/laharic fan can be seen.

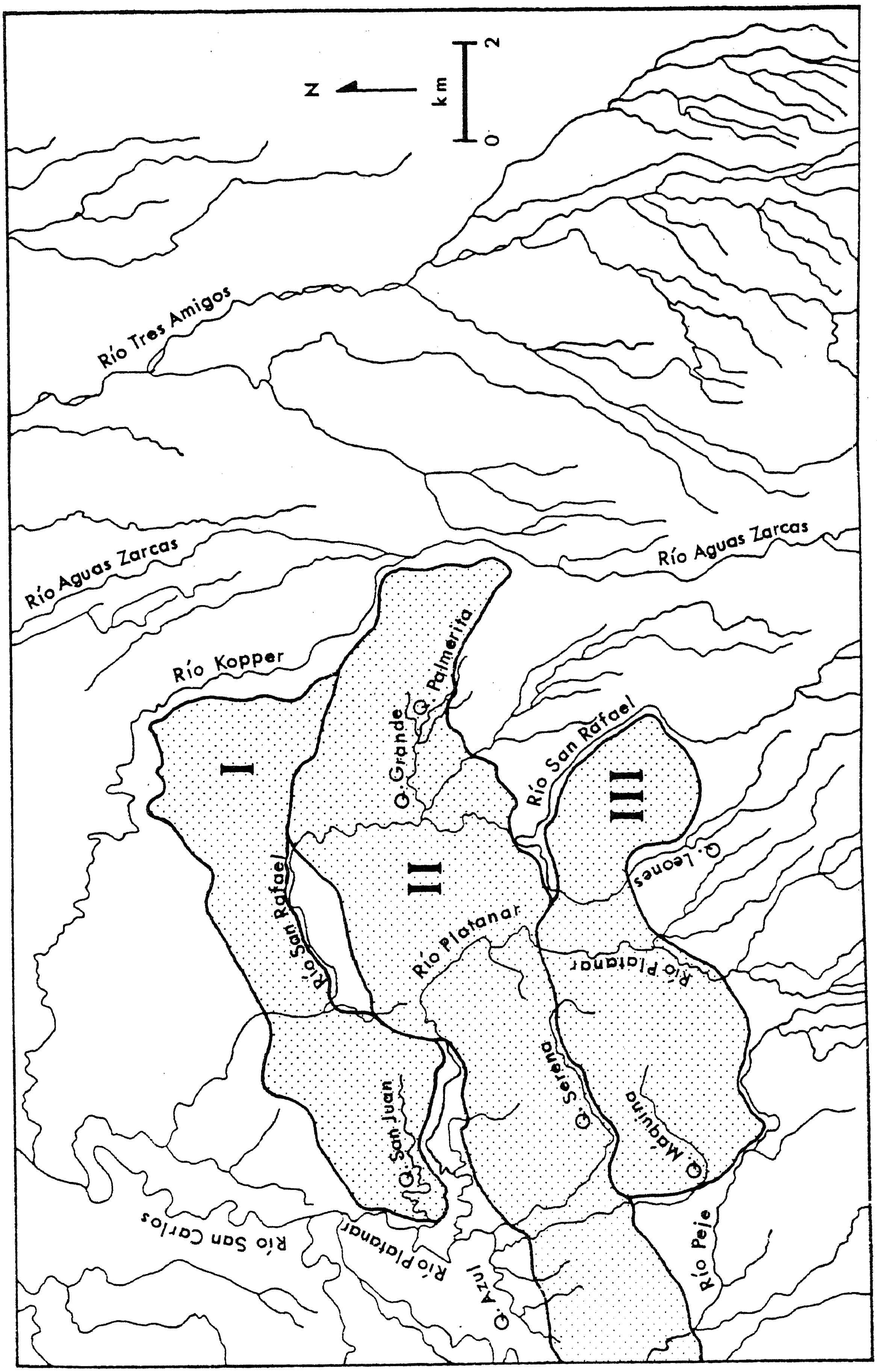
portion of the massive landslide apparently was caused by undercutting of the Río San Rafael, which skirts along the base of fault scarp III. Accelerated formation of slumps, which are most conspicuous in cleared areas on the lower portion of the massive landslide, probably resulted from removal of the protective forest cover.

Drainage Patterns

Drainage patterns frequently are very useful in the interpretation of landforms, since they reflect such factors as initial slope of the terrain, differences in rock resistance to weathering and erosion, structural control, and recent diastrophism (Thornbury, 1969, p. 119). In tectonically active areas, the drainage pattern often is characterized by multiple, nearly right-angled offsettings of stream courses because streams, following the path of least resistance, tend to flow along rather than across faults.

Most major streams and their large tributaries which traverse the Piedmont Province of southern San Carlos originate as consequent streams on the slopes of three large volcanoes in the Mountainous Province of San Carlos, where they form a radial drainage pattern typical of volcanic cones. In the Piedmont Province of southern San Carlos, two distinct, spatially segregated drainage patterns have evolved. In the eastern part of the area, streams form a dendritic drainage pattern; in contrast, multiple, nearly right-angled offsettings of stream courses have occurred in the central and western parts of the area where the escarpments are located. This evidence strongly suggests that the escarpments are fault scarps and that the ridges they bound are fault blocks. Stream courses are controlled by the bases of both front scarps and backslopes of the ridges (Fig. 14).

Fig. 14.--Drainage patterns in the Piedmont Province and adjacent portions of the Atlantic Lowland and Mountainous Provinces of southern San Carlos. The extent of the three tilted fault-block ridges in the western and central parts of the Piedmont Province of the study area is indicated by a dotted pattern and the Roman numerals I, II, and III. In those parts of the Piedmont Province where the tilted fault-block ridges are located note: (1) the multiple, nearly right-angled offsettings of stream courses, which are strongly suggestive of faulting; (2) the small number of antecedent streams, which were able to maintain their courses during the formation of the ridges; and (3) the relatively low drainage density, which suggests a disruption of smaller stream courses and the passage of insufficient time since the occurrence of tectonic movements to permit the establishment of a new, well-established drainage system.


N
km
0
2
Río Tres Amigos
Río Aguas Zarcas
Río Aguas Zarcas
Río Kopper
Q. Palmerita
Q. Grande
Río San Rafael
Río San Rafael
I
II
III
Q. Leones
Río Platanar
Río Platanar
Río Platanar
Q. Serena
Q. San Juan
Q. Maquina
Río San Carlos
Q. Azul
Río Peje

The drainage pattern in the western and central parts of the Piedmont Province also allows inferences about the speed and age of tectonic movements. The fact that only large streams were able to maintain their courses during uplift suggests that tectonic movements were sufficiently fast to disrupt the courses of smaller streams. Moreover, uplift appears to have been continual rather than episodic in nature, since major breaks in the longitudinal profiles of antecedent streams and terraces along antecedent stream valleys are lacking. Furthermore, the persistence of a relatively low drainage density suggests that insufficient time has elapsed since tectonic movements took place to permit the establishment of a new, well-established drainage system.

Triangular Facets on Spur Ends

In the humid tropics, triangular facets on spur ends are expected to occur only along relatively recent fault scarps because of the rapid alteration of steep slopes by mass-wasting and fluvial processes. Along the fault scarps in the Piedmont Province of southern San Carlos clearly defined triangular facets on spur ends are scarce, suggesting that tectonic movements which led to the formation of these landforms took place at some time in the past.

The best examples of triangular facets on spur ends were observed along the central portion of fault scarp II, in the area where the Río San Rafael emerges from tilted fault-block ridge II, and along a low, 20 m high escarpment formed along a fault splinter, which rises approximately 750 m in front of the main scarp at this locality (Fig. 15).

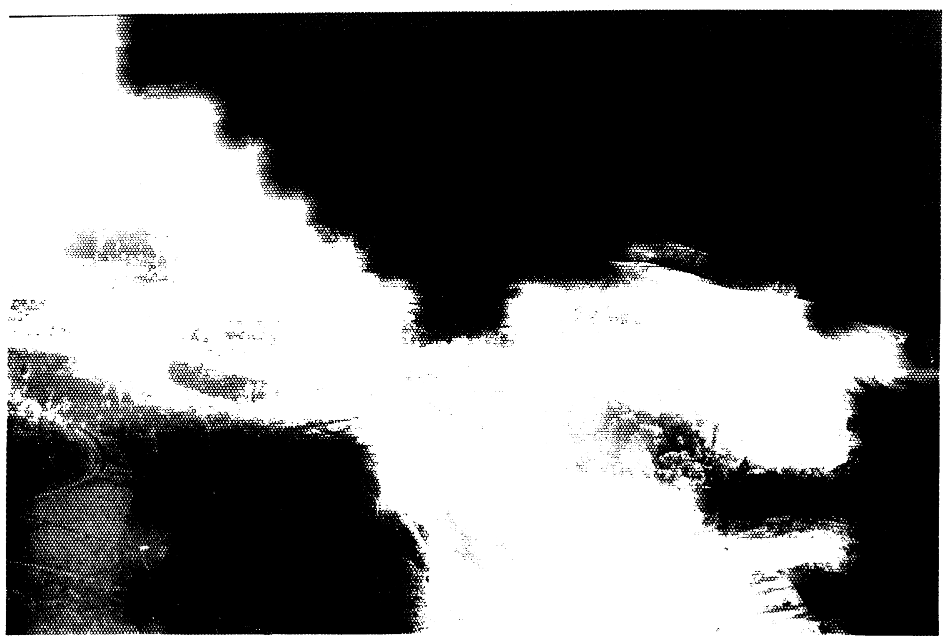


Fig. 15.--Triangular facets on spur ends along fault scarp II, and along a low escarpment in front of the main scarp, in the area where the Río San Rafael emerges from tilted fault-block ridge II. Note the small alluvial plain between the two fault scarps, which was built up by the Río San Rafael. On the right side of the alluvial plain, an abandoned meander of the stream is recognizable.

The relatively well-preserved triangular facets on spur ends suggest relative recency of tectonic movements. On the other hand, faulting occurred sufficiently back in time to permit the buildup of a small alluvial plain in the area between the two fault scarps.

Hot Springs

The tectonic origin of an escarpment may be indicated by the emergence of hot springs at its base. In the Piedmont Province of southern San Carlos, hot springs are present at the base of tilted fault-block ridge III near the eastern end of the ridge at a locality appropriately named Aguas Calientes (Hot Waters).

The emergence of hot springs in the vicinity of Aguas Calientes may provide evidence for faulting but could also be related to volcanism, since a lava flow terminates about 100 m to the south. On the other hand, other springs which were observed along the base of the same lava flow about 1 km northeast of Aguas Calientes exclusively contained cold water.

Wind Gaps

Notches along ridge crests that are controlled neither by lithology nor caused by fluvial erosion point to a tectonic origin of ridges. The notches represent wind gaps, which were created when faulting and uplift disrupted former stream courses. Along the crests of tilted fault-block ridges in the Piedmont Province of southern San Carlos major breaks are limited to a few water gaps, where antecedent streams maintained their courses during uplift (Fig. 16). On the other hand, numerous small notches are present along the crests of the ridges (Fig. 17).

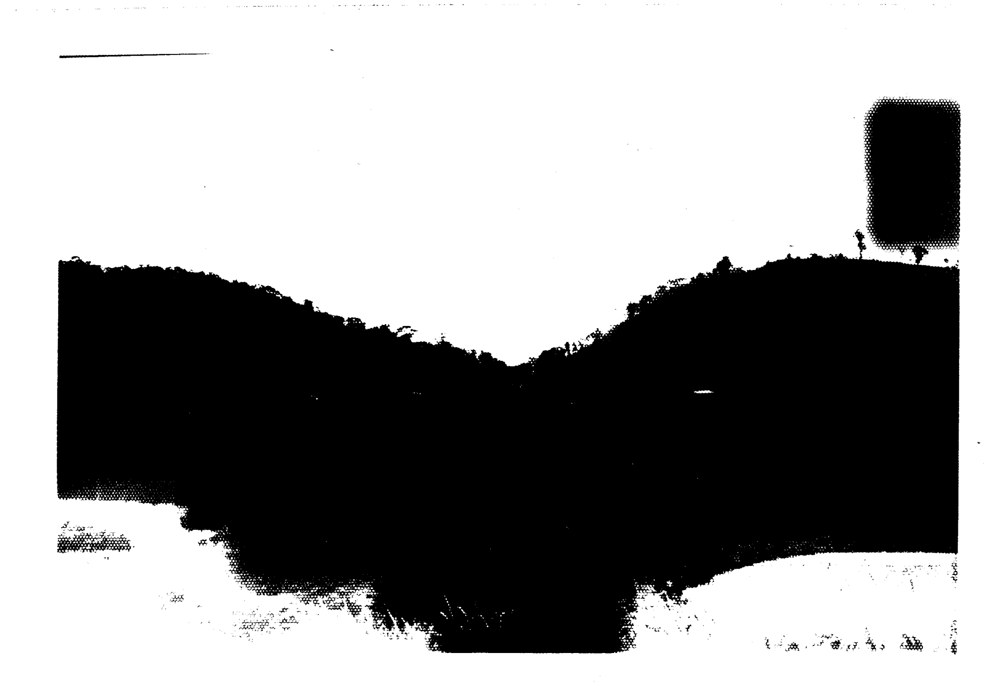


Fig. 16.--Westcentral portion of tilted fault-block ridge III, viewed from the south. Note the major, V-shaped break in the ridge, representing a water gap created by the Río Platanar, an antecedent stream.

Fig. 17.--Front scarp of tilted fault-block ridge II, viewed from the village of San Rafael. Note the numerous small notches along the crest of the ridge. In the foreground, floodplain of the Río San Rafael.

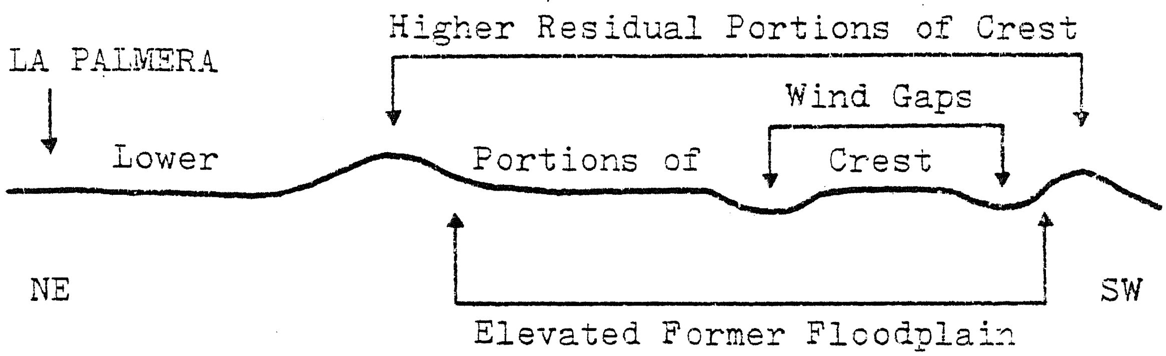


Fig. 18.--Crestline of tilted fault-block ridge II west of the village of La Palmera, viewed from a small outlier located north of the ridge. Note the small, residual, higher and the more extensive, uniformly flat, lower portions of the crest. In the latter, two small notches, believed to be wind gaps, are incised.

One area in which two small notches were investigated extends along the crest of tilted fault-block ridge II west of the village of La Palmera. Although small creeks originate below these notches on either side of the ridge, no evidence of running water was detected in the notches themselves. This seems to preclude their formation by headward fluvial erosion and to suggest that the notches are wind gaps, representing abandoned stream channels in an elevated former floodplain (Fig. 18).

Circumstantial evidence for a pre-tectonic origin of the two notches is provided by the presence of alluvium on the very top of a small outlier north of the ridge. The coarse-textured, bouldery alluvium is in direct alignment with and occurs at about the same elevation as the two notches. As the formation of the notches, the deposition of the alluvium must have taken place prior to the occurrence of tectonic displacements in the area.

Although it would have been desirable to establish the origin of other small notches along the crests of tilted fault-block ridges, it is postulated that many of these notches are wind gaps. The nature of the drainage pattern in the western and central parts of the Piedmont Province, which clearly shows a disruption of smaller stream courses as a result of tectonic movements, lends strong support to this mode of origin.

Alluvial/Laharic Fans and Alluvial Plains

Although alluvial fans are most commonly associated with arid and semiarid climatic environments, they often are prominent landforms in the humid tropics. They tend to build up at the foot of mountains where high-gradient tropical streams debouch onto surrounding flatter terrain. In the Piedmont Province of southern San Carlos, several alluvial fans of varying sizes are present. Almost without exception, the alluvium in these fans is interbedded with or overlain by laharic deposits. Therefore, it seems appropriate to refer to them as alluvial/laharic fans. In the following discussion, the designation alluvial/laharic fan is understood rather than stated each time.

The largest and easternmost fan, referred to as the Aguas Zarcas (alluvial/laharic) fan, has built up where the Río Aguas Zarcas emerges from mountainous terrain about 3 km south of the village of Aguas Zarcas. Another large fan, referred to as the La Marina (alluvial/laharic) fan, is present between the eastern portions of tilted fault-block ridges II and III west of the present-day channel of the Río Aguas Zarcas. Two other fans, located southwest of the La Marina fan, extend between the backslope of tilted fault-block ridge III and the edges of lobate lava flows that form the southern boundary of the Piedmont Province. The larger of these fans, referred to as the Quesada (alluvial/laharic) fan, is located southwest of a recent andesitic lava flow that separates the two fans. The smaller of these fans, referred to as the Tessalia (alluvial/laharic) fan, is located northeast of this lava flow. In the southwestern part of the Piedmont Province, two coalescing fans, built up by the Río Peje and the Río La Vieja, abut on the backslope of tilted fault-block ridge II. These landforms are referred to as the Río Peje/Río La Vieja (alluvial/laharic) bajada. In the northcentral part of the Piedmont Province, two small alluvial plains are associated with the Río Platanar and the Río San Rafael (Fig. 19).

<u>Aguas Zarcas Alluvial/Laharic Fan</u>

The compound Aguas Zarcas fan was built up mainly by the Río Aguas Zarcas and to a lesser degree by the Río Negritos and some of its tributaries. The apex of the fan lies at an elevation of about 700 m. The upper portion of the fan is bounded by the present-day channel of the Río Aguas Zarcas in the west and by the Río Negritos and two of its tributaries in the east. The lower portion of the fan is delineated clearly only in the west, where it borders on tilted fault-block ridges II and I. To the north and north-

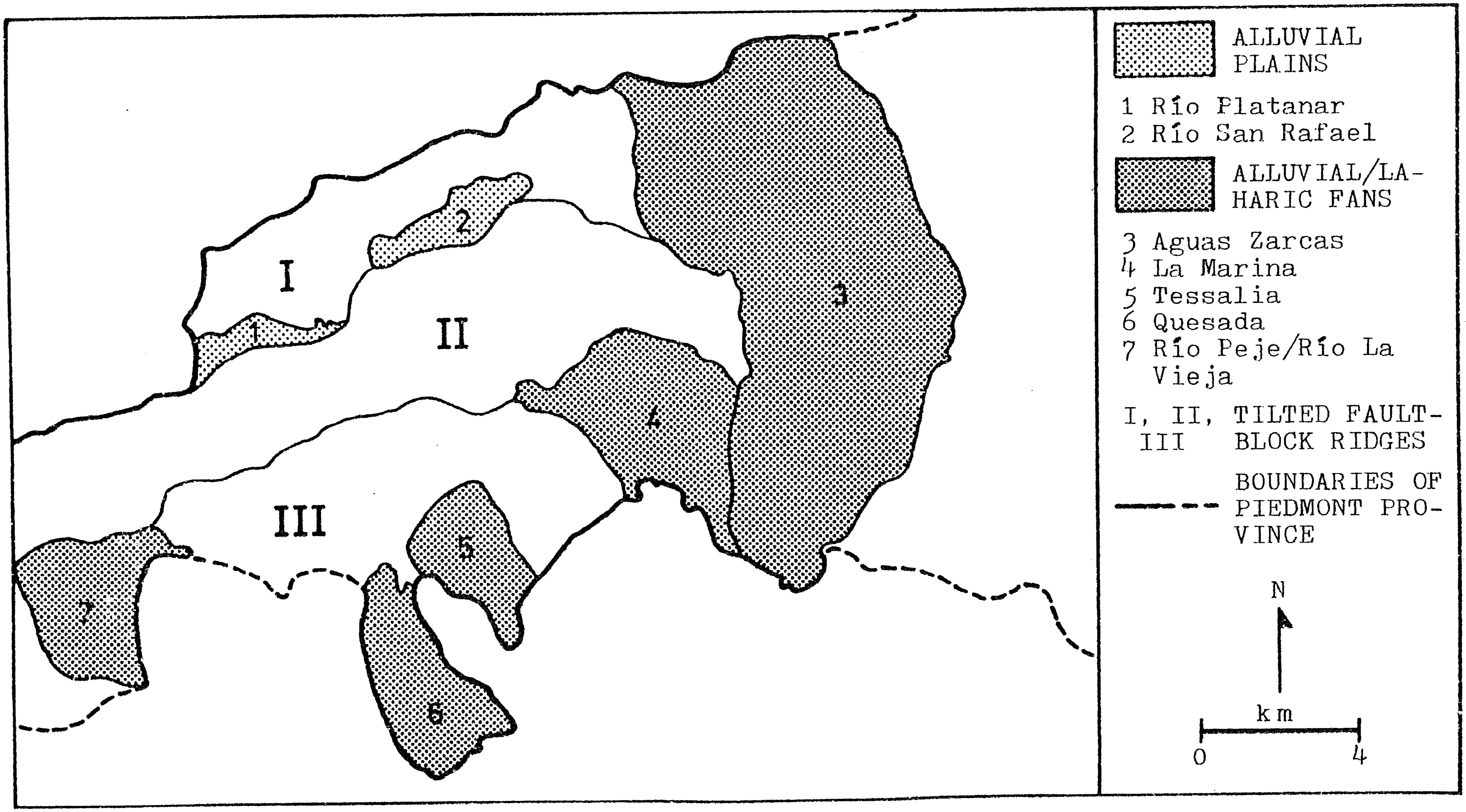


Fig. 19.--Spatial distribution of alluvial/laharic fans and alluvial plains in the Piedmont Province of southern San Carlos. East and west boundaries of the area are arbitrary north-south lines.

east, the fan extends for varying distances, its distal end merging with landforms in the Atlantic Lowland Province and with landforms in the eastern part of the Piedmont Province, respectively (Fig. 20).

As is typical of fan surfaces, slope angles are smaller on the lower than on the upper portion of the Aguas Zarcas fan. On the lower northern and northwestern portions of the fan, slope angles, as measured along the road from Los Chiles to Los Llanos, gradually decrease from 3° to less than 1° north of Vuelta de Kopper. On the lower north-eastern part of the fan, slope angles, as measured along the road to Pital that branches off north of Los Chiles, initially are 3°, decrease to 2°, and finally are only 0.5° at the Quebrada Los Pericos. In contrast to the gradual decrease in slope steepness on the lower portion of the Aguas Zarcas fan, slope angles vary by one or more degrees within relatively short distances on the upper portion of the fan. On the lower upper portion of the fan, slope angles, as measured along the road between Aguas Zarcas and Los Chiles, generally vary between 3° and 5°. However, just south of Los Chiles, where the road crosses the Quebrada Campamento, the slope of the fan steepens to 14°. Similar abrupt breaks in slope are evident between Aguas Zarcas and the apex of the fan (Fig. 21; also Fig. 20 for localities).

In contrast to a progressive decrease in the size of fan materials which generally occurs with distance from the

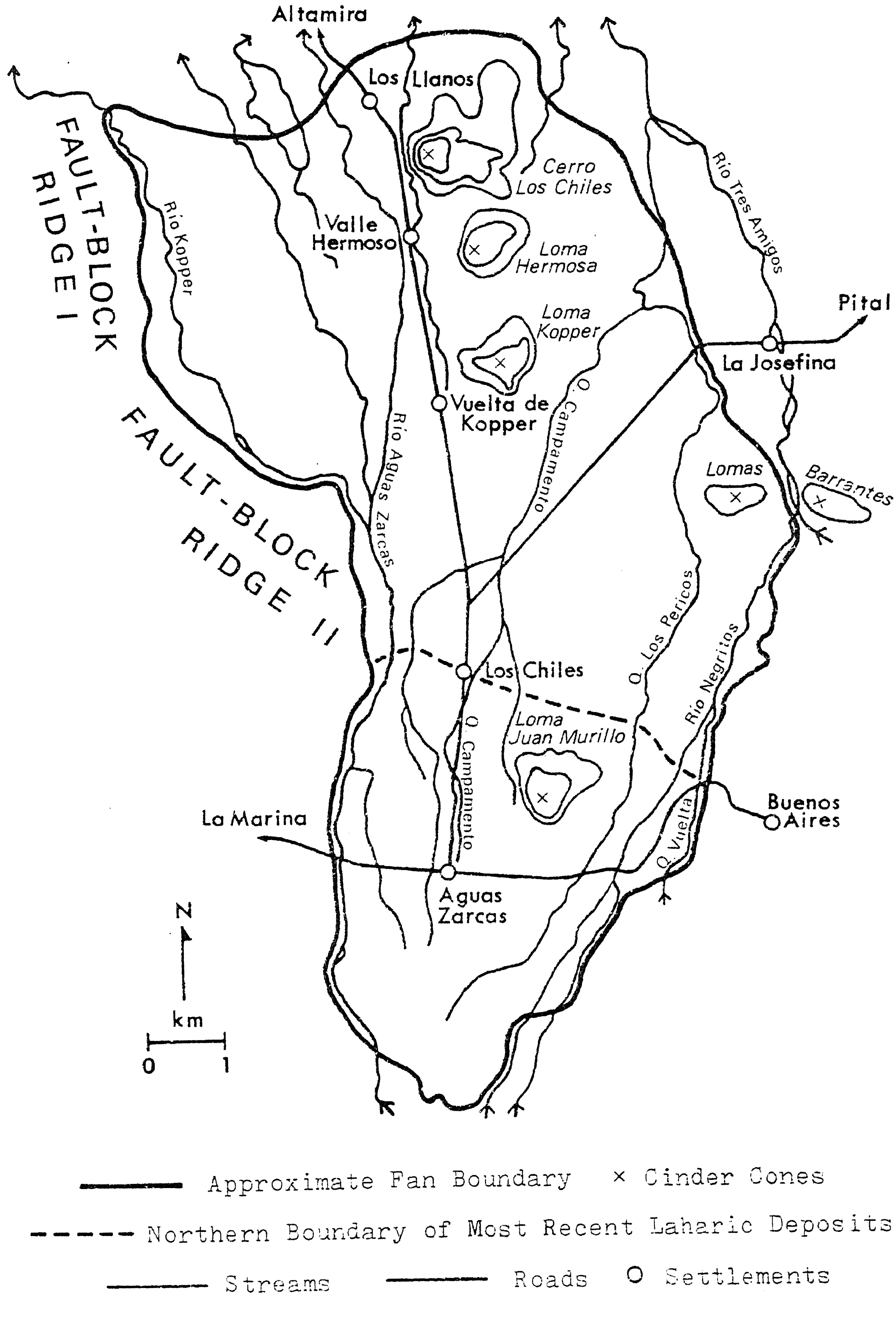


Fig. 20.--Aguas Zarcas alluvial/laharic fan.

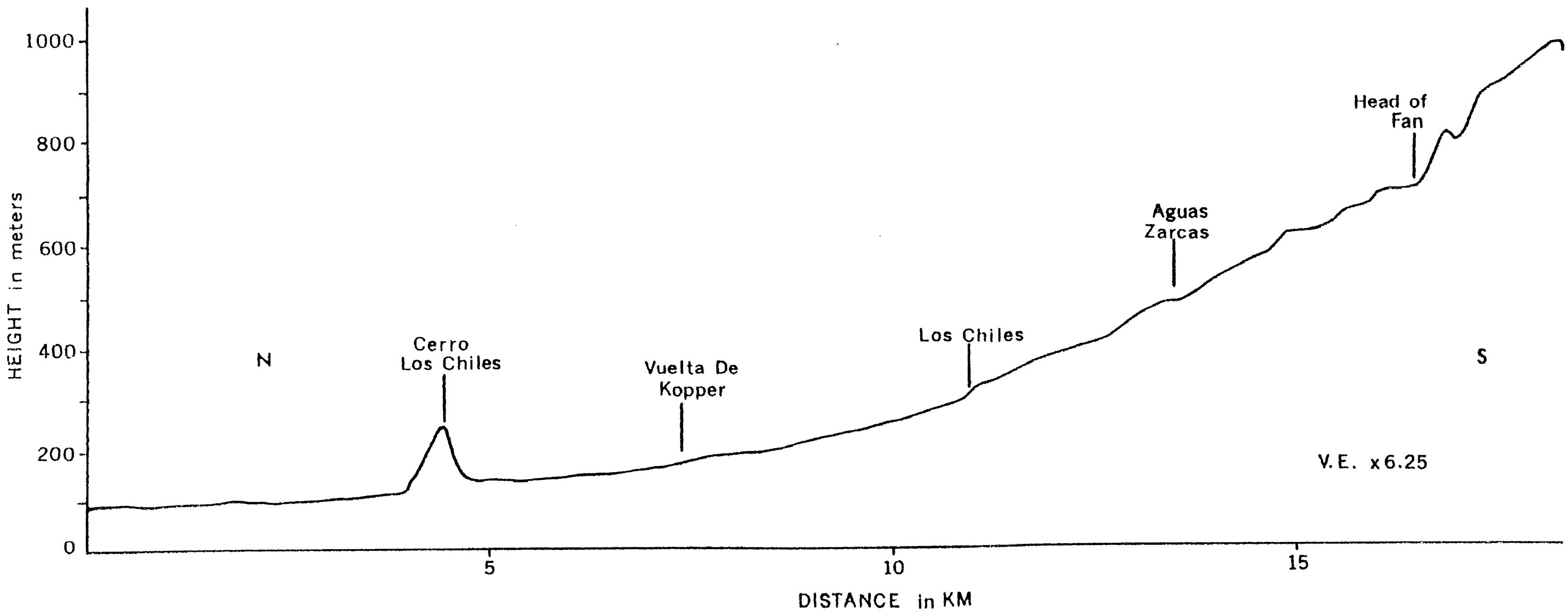


Fig. 21.--Topographic profile showing the slope of the Aguas Zarcas alluvial/laharic fan. The profile was drawn along the 499,000mE UTM grid line on the Aguas Zarcas topographic sheet (Appendix IV). It is bounded by the 275,000mN UTM grid line in the north and by the 257,050mN UTM grid line in the south.

apices of fans, a sudden change in the size and nature of fan sediments takes place on the Aguas Zarcas fan. This change coincides with an abrupt break in slope which, for example, was noted at Los Chiles below the fan segment on which the slope angle was measured to be 14°. The break in slope can be traced across the width of the Aguas Zarcas fan and marks the boundary between two distinctly different surface deposits on the upper and lower portions of the fan (Fig. 20).

The upper portion of the Aguas Zarcas fan is characterized by a hummocky surface topography and unstratified, poorly sorted surface deposits which contain a high proportion of subangular to subrounded rock fragments of varying sizes (Fig. 22). In many places, boulders protrude through the fan surface. They are especially conspicuous in small depressions and along small, ephemeral water courses where sheetwash and fluvial erosion have preferentially removed some of the finer fan sediments (Fig. 23). Most boulders are andesitic in composition, although a small number of basaltic boulders are intermixed with andesitic boulders at some localities. Exposed surfaces of protruding boulders have acquired dark gray patinas under which they are essentially unaltered.

The described textural characteristics of surface deposits on the upper portion of the Aguas Zarcas fan are typical of laharic deposits (Bull, 1964, p. 23, 31; Crandell, 1968, p. 764; 1971, p. 6-7; Mullineaux and

Fig. 22.--Upper portion of the Aguas Zarcas fan south of the village of Aguas Zarcas. Note the hummocky topography of the fan and the high proportion of subangular to subrounded clasts of varying sizes in the fan surface deposits.

Fig. 23.--Subrounded andesitic boulders of varying sizes protruding through the surface of the Aguas Zarcas fan in a depression south of the village of Los Chiles. Beneath the dark gray patina boulders are essentially unaltered.

Crandell, 1962, p. 857). Moreover, the argument for a laharic origin of the deposits is strengthened by a non-random orientation of protruding boulders (Fig. 24).

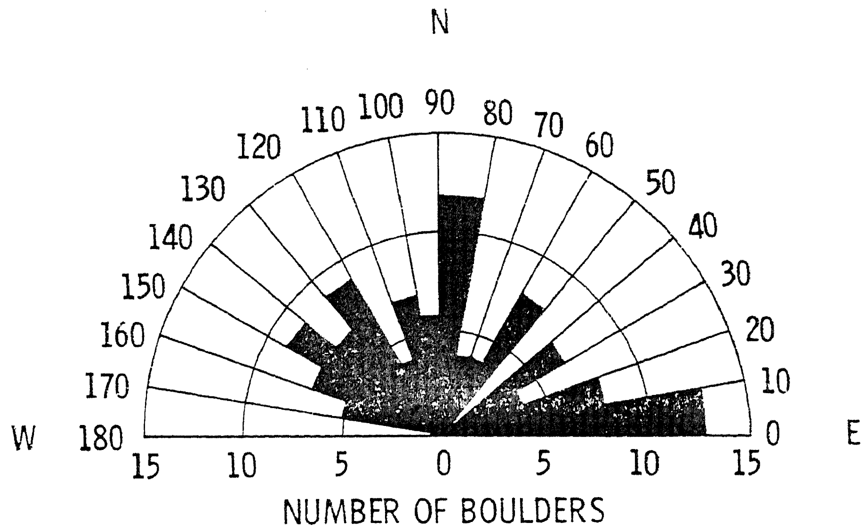


Fig. 24.--Rose diagram showing a non-random orientation of the long-axes of 115 protruding boulders of varying sizes, which were randomly selected in a small surface depression south of the village of Los Chiles on the upper portion of the Aguas Zarcas fan. Note two modes of boulder orientation, which are related to variations in the size of clasts. Large boulders generally point north-northwest in the downslope direction of the Aguas Zarcas fan.

Once lahars spread out at the mouth of stream valleys and begin to travel by the manner of laminar flow, they rapidly develop a clast fabric in which the long-axes of most rock fragments parallel the direction of flow (Lindsay, 1968, p. 1244, 1247). The orientation forces will act more quickly on larger clasts (Lindsay, 1968, p. 1248), which may explain why two modes of boulder orientation are recognizable on the Aguas Zarcas fan. Large boulders are generally oriented parallel to the slope of the fan, pointing north-northwest in the downslope direction of the fan.

Surface deposits on the lower portion of the Aguas Zarcas fan lack the concentration of large subangular to subrounded boulders, generally contain much fewer coarse rock fragments than the surface deposits on the upper portion of the fan, and are notably stratified. These characteristics suggest that they are of alluvial rather than of laharic origin.

La Marina Alluvial/Laharic Fan

The La Marina fan, which adjoins the Aguas Zarcas fan in the west, is the second largest alluvial/laharic fan in the Piedmont Province of southern San Carlos (Fig. 19). In the east, the fan is bounded by the present-day channel of the Río Aguas Zarcas. In the west, the Río San Rafael, skirting around the base of the front scarp of tilted fault-block ridge III, marks its boundary. In the north and northwest, the distal end of the fan rests against the base of the backslope of tilted fault-block ridge II. The upper portion of the fan is partially buried by lava flows, dividing the apex of the fan into two parts: in the east, the fan originates where the Quebrada Zapotal and the Río La Ceiba emerge from mountainous terrain; in the west, it commences at the base of a lava flow about 1 km south of the Hda. La Marina (Figs. 25 and 26).

Slope angles are relatively uniform over the entire width and length of the La Marina fan, decreasing from 5° on the upper to 3° on the lower portion of the fan (Fig. 27).

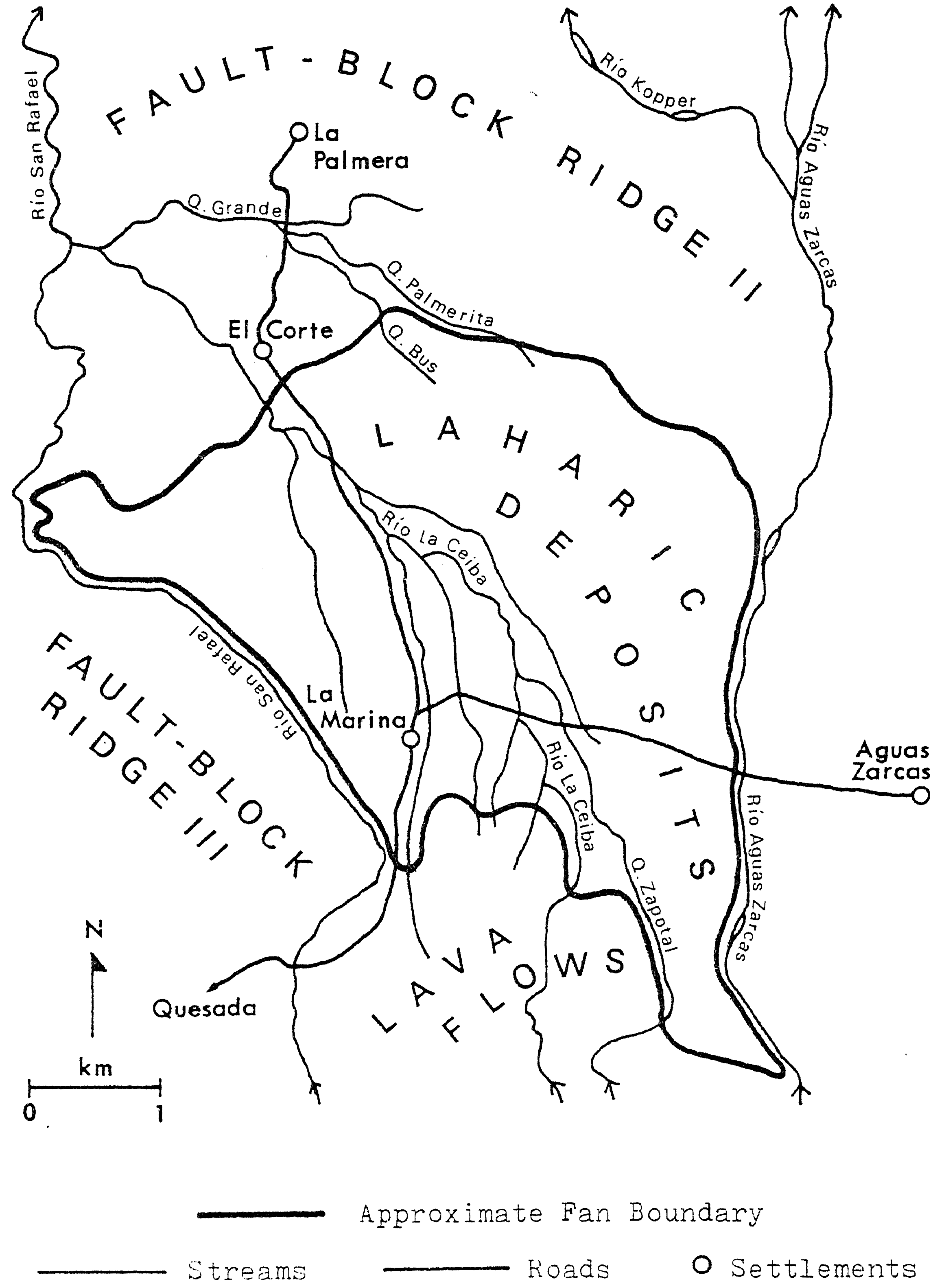


Fig. 25.--La Marina alluvial/laharic fan.

Fig. 26.--Oblique aerial view of the upper and west-central portions of the La Marina fan. In the center background, note the cleared lower part of the westernmost tongue of the lava flows which partially buried the upper portion of the fan. The forested ridge in the right center is tilted fault-block ridge III. The Hda. La Marina is located in the upper center. The tree-lined stream in the left center and foreground is the Río La Ceiba.

On the other hand, fan surface materials are distinctly different on the eastern and western portions of the fan. Surface deposits on the eastern portion of the fan, which are unstratified and contain numerous large subangular to subrounded boulders to a depth in excess of 9.5 m, as observed in exposures along the left bank of the Río Aguas Zarcas, are laharic in origin. In contrast, surface deposits on the western portion of the fan, which show a marked stratification and lack large rock fragments, are alluvial in origin. The boundary between the two differing types of surface deposits is abrupt and coincides with the

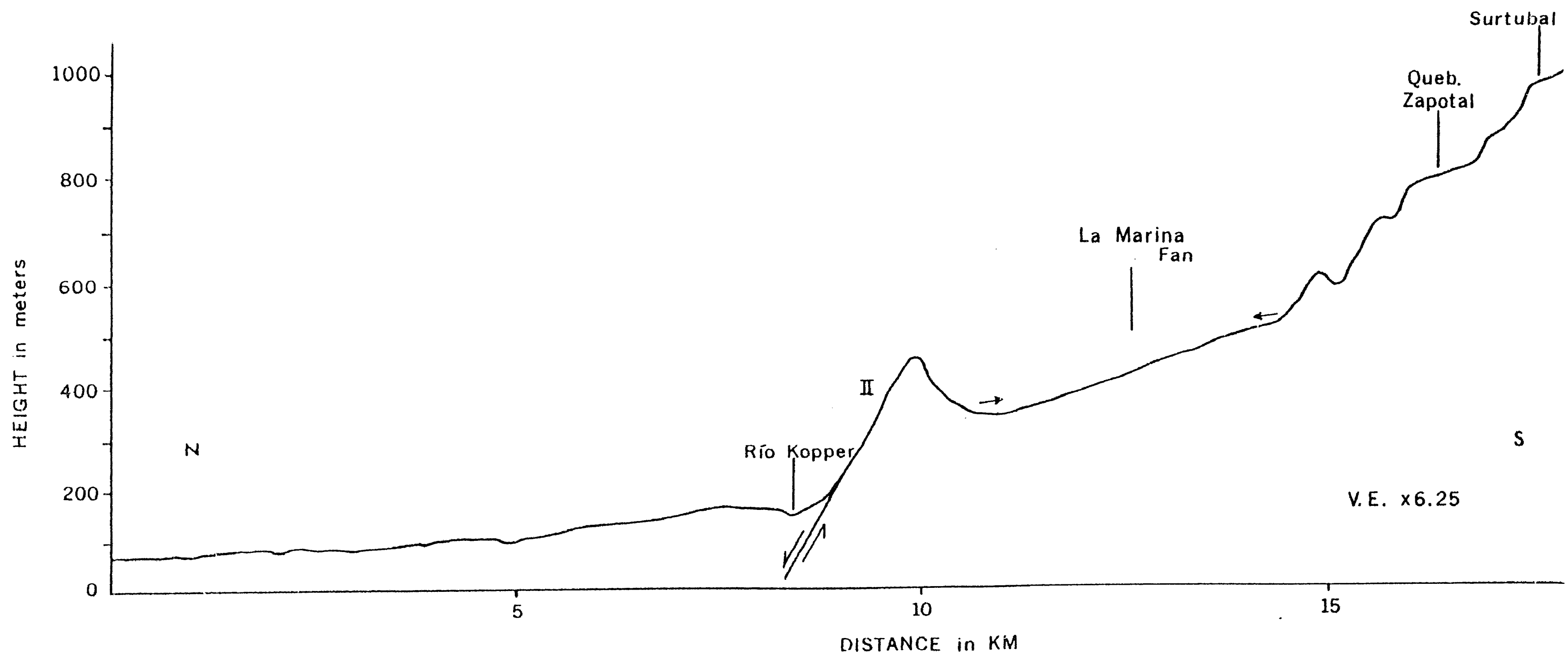


Fig. 27.--Topographic profile showing the slope of the eastern portion of the La Marina fan and the slopes of adjacent landforms. The profile was drawn along the 497,000^{m}E UTM grid line on the Aguas Zarcas topographic sheet (Appendix IV). It is bounded by the 275,000^{m}N UTM grid line in the north and by the 257,050^{m}N UTM grid line in the south.

easternmost tributary of the Río La Ceiba (Fig. 25).

In areas where lahars come to rest major changes in the preexisting drainage pattern frequently take place (Geikie, 1903, p. 312). Large-scale stream derangements are not uncommon. There is evidence that the lahar which spread out on the eastern portion of the La Marina fan caused the partial burial of a former channel of the Río Aguas Zarcas. The lower, beheaded part of the former Aguas Zarcas stream valley extends from the northcentral end of the La Marina fan to the junction of the Río La Ceiba with the Río San Rafael (Fig. 25). Since the upper part of the valley is partially filled with laharic deposits, the large size of the valley is more readily apparent in its central and lower sections. The streams which currently occupy the valley, including the Quebrada Grande and its tributaries Quebradas Palmerita and Bus, are far too small to have created the valley nor do they seem capable of having transported the large rounded boulders which are present on the valley floor. It is also unlikely that they produced the residual terrace which occurs at 16.5 m along the valley walls since other terraces are found close to stream channels at only 1.5 m and 3.0 m along the Quebrada Palmerita and at 4.5 m along the Quebrada Grande (Fig. 28). Derangement of the Río Aguas Zarcas by the lahars which descended upon the eastern portion of the La Marina fan is not an improbable event and best explains the presence of misfit streams in the relatively large valley which extends

Fig. 28.--Southern portion of the westcentral part of the former valley of the Río Aguas Zarcas, as viewed from the road that connects the villages of El Corte and La Palmera. In the center background, a recent landslide scar is visible through the trees on the right side of the former Aguas Zarcas stream valley. In the left center, note the tree-lined present bed of the Quebrada Palmerita. To the right of the creek, its first terrace at 1.5 m extends from the foreground into the far center; its second terrace at 3.0 m can be followed from the right center to the far center. The chickens in the foreground are browsing on the tread of the first terrace; the house in the right center is being constructed on the tread of the second terrace.

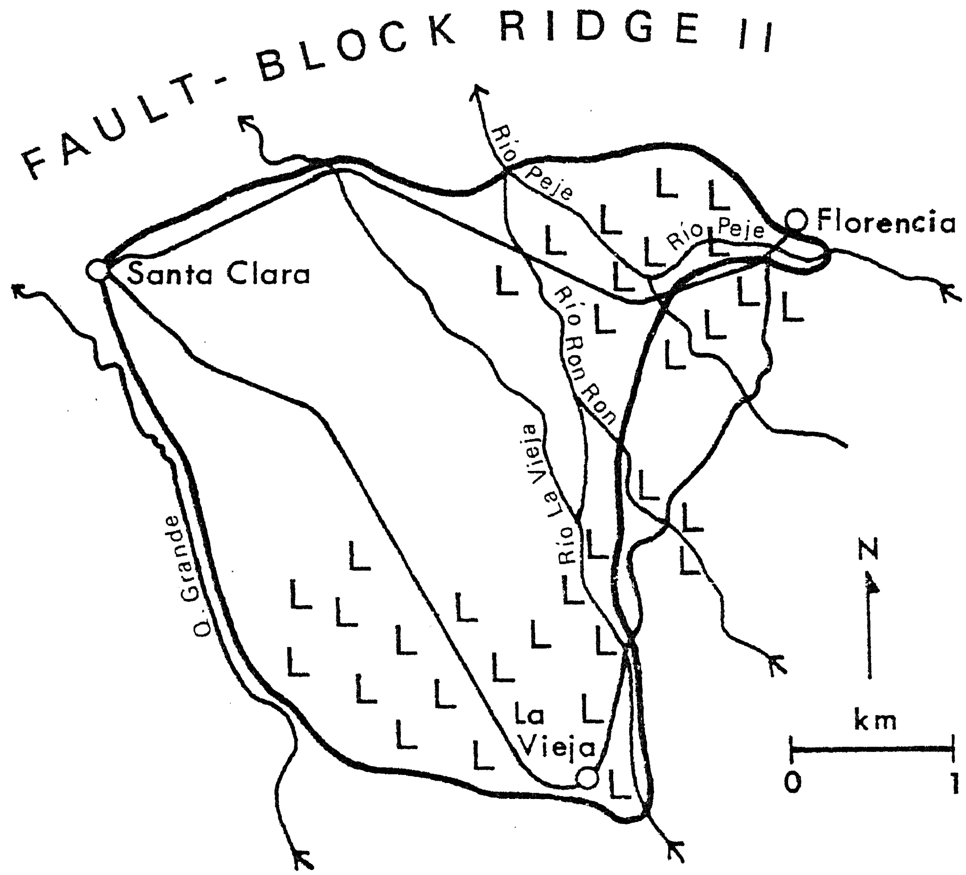
along the backslope of tilted fault-block ridge II northwest of the fan.

Río Peje/Río La Vieja Alluvial/Laharic Bajada

The Río Peje/Río La Vieja bajada, located in the southwestern part of the Piedmont Province of southern San Carlos (Fig. 19), consists of two coalescing fans which built up against the backslope of tilted fault-block ridge II where the Río Peje and the Río La Vieja emerge from higher terrain (Fig. 29).

On the upper portions of both fans, extensive laharic surface deposits are present, extending for 2 km or more downslope from the apices of the fans (Fig. 29). As the laharic surface deposits on the Aguas Zarcas and La Marina fans, the deposits are unstratified, poorly sorted, and contain a high proportion of coarse rock fragments of varying sizes. Large subangular to subrounded boulders, protruding through the surface of the deposits, are very common. They are most conspicuous near the apices of the fans, but linear concentrations of boulders, believed to have been excavated by sheetwash and fluvial erosion along ephemeral water courses and small streams, are traceable over appreciable distances downslope (Figs. 30 and 31). The large size of the boulders and their occurrence on very gently sloping terrain lend strong support to a laharic origin of the deposits.

Boulder orientation measurements indicate that the lahar which descended upon the upper portion of the Río La Vieja fan travelled in a northwesterly direction after emerging from the mountainous reach of the Río La Vieja (Fig. 32). As on the La Marina fan, laharic deposition caused major changes in the preexisting drainag pattern of the area. Evidence for the derangement of former stream courses is provided by an almost complete lack of permanent streams on the western portion of the Río La Vieja fan and by the apparent diversion of the Río La Vieja to its present



Approximate Fan Boundary

Streams   Roads   O Settlements

L Observed Laharic Surface Deposits

Fig. 29.--Río Peje/Río La Vieja bajada.

Fig. 30.--Concentration of large subrounded boulders at the surface of laharic deposits northwest of the village of La Vieja, 1.7 km downslope from the apex of the Río La Vieja fan. Note that the slope of the terrain is only 2°.

Fig. 31.--Laharic surface deposits near the apex of the Río Peje fan. In the background, note the linear concentration of boulders along the outside bend of a small stream, believed to have resulted from preferential removal of matrix fines by sheetwash and fluvial erosion.

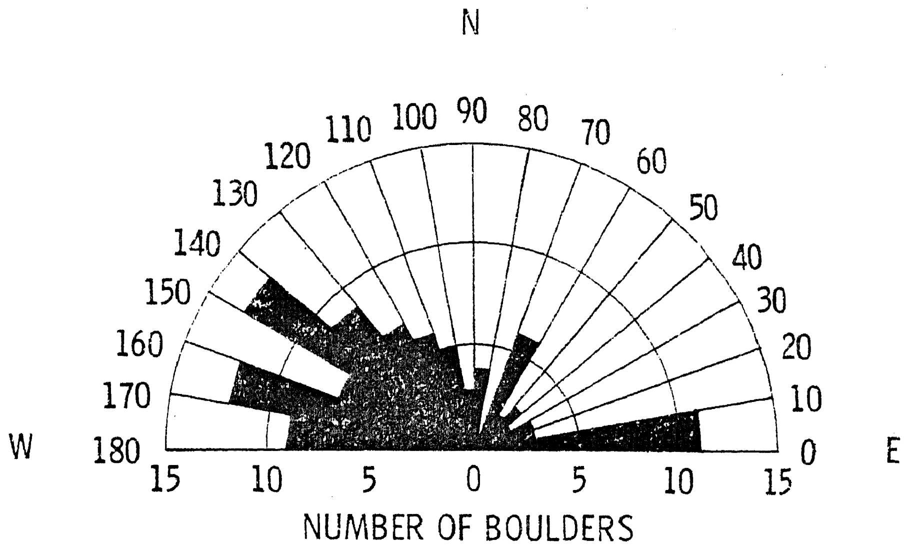


Fig. 32.--Rose diagram showing the orientation of the long-axes of 103 randomly selected boulders of varying sizes exposed at the surface of laharic deposits on the upper portion of the Río La Vieja fan. Note that most boulders point west-northwest.

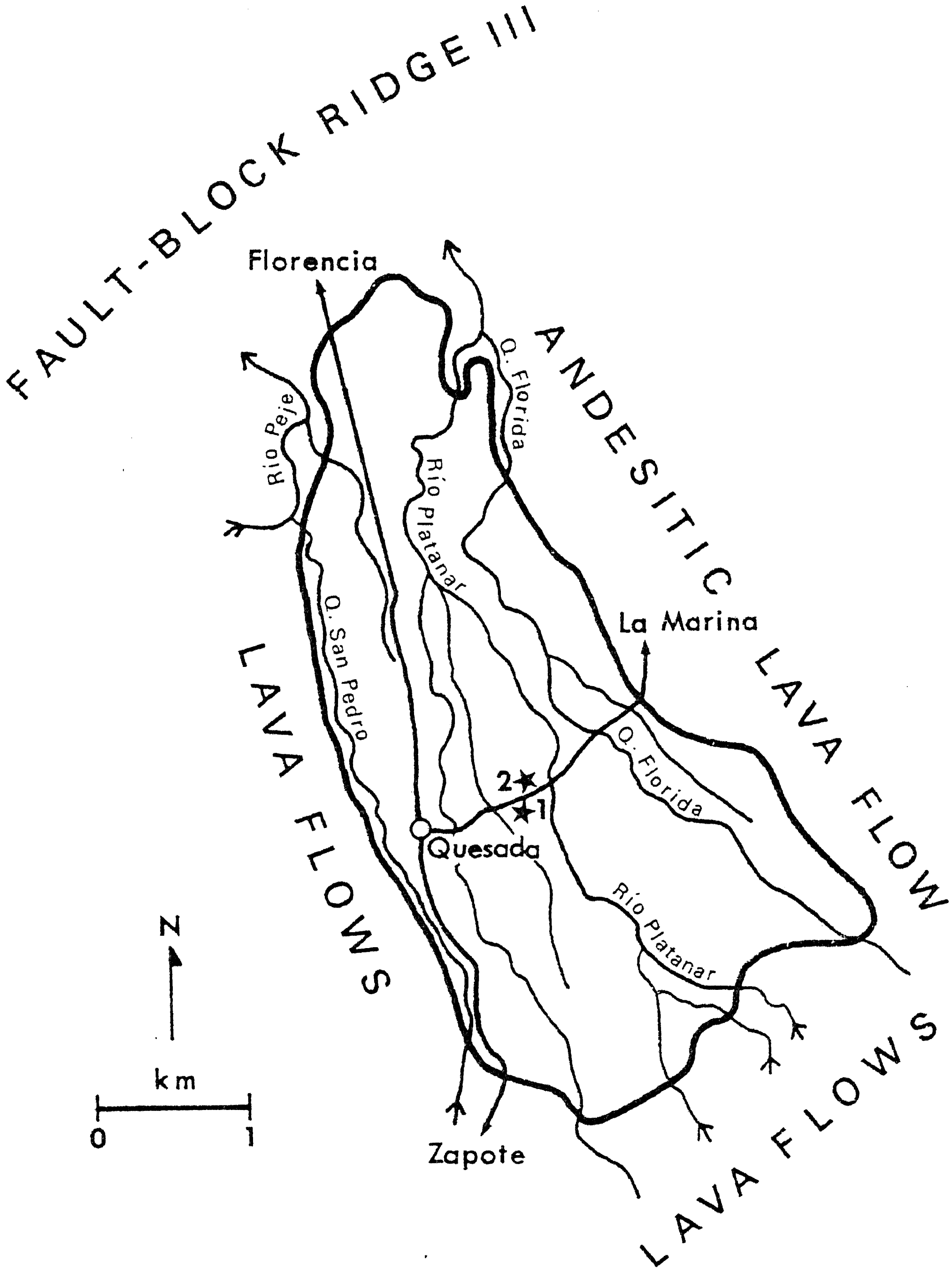
course along the eastern margin of the fan. A still existing high-water connection of the Río La Vieja with the Río Peje drainage system via a branch that joins the Río Ron Ron about 2 km north of the apex of the fan probably was created before the stream established its new, permanent northwesterly course (Fig. 29)

Quesada Alluvial/Laharic Fan

The Quesada fan, located in southcentral part of the Piedmont Province of southern San Carlos (Fig. 19), was built up by the Río Platanar and its larger tributaries. The upper portion of the fan consists of two small coalescing fans which head at elevations of slightly above 800 m at the bases of lava flows that form the southern boundary of the study area. Lava flows also mark the eastern and western boundaries of the fan. In the north, the distal end of the fan rests against the backslope of tilted fault-block ridge III (Fig. 33). The shape of the fan is somewhat unusual in that the fan narrows from a width of about 2.5 km on the upper portion to less than 1 km near the end. This configuration has arisen because the fan is hemmed in on both sides by lava flows, which prevented normal fan development.

In contrast to a general lack of large vertical exposures on the other fans in the Piedmont Province of southern San Carlos, several excellent exposures are present on the Quesada fan. Two sections, located about 900 m east of the center of Ciudad Quesada along the road that leads to La Marina (Fig. 33), allowed detailed stratigraphic studies of the upper 5 m of fan deposits. In Section 1, located on the south side of the road, four depositional units are exposed. In Section 2, located in the entrance way of a house on the north side of the road, five depositional units are recognizable. Although the thickness of individual units differs slightly in the two sections, correlation between them is possible without difficulty (Fig. 34).

Unit I, which is absent from Section 1 and only present in Section 2, varies in thickness between 45 and 65 cm. It has a sandy loam texture and dark brown color (7.5YR 3/2) which grades into dark yellowish brown (10YR 3/4) near the bottom of the unit. The latter is marked by the presence of rounded to subangular, partially decomposed, andesitic



Approximate Fan Boundary

Streams Roads O Settlements

✶ Stratigraphic Sections

Fig. 33.--Quesada alluvial/laharic fan.

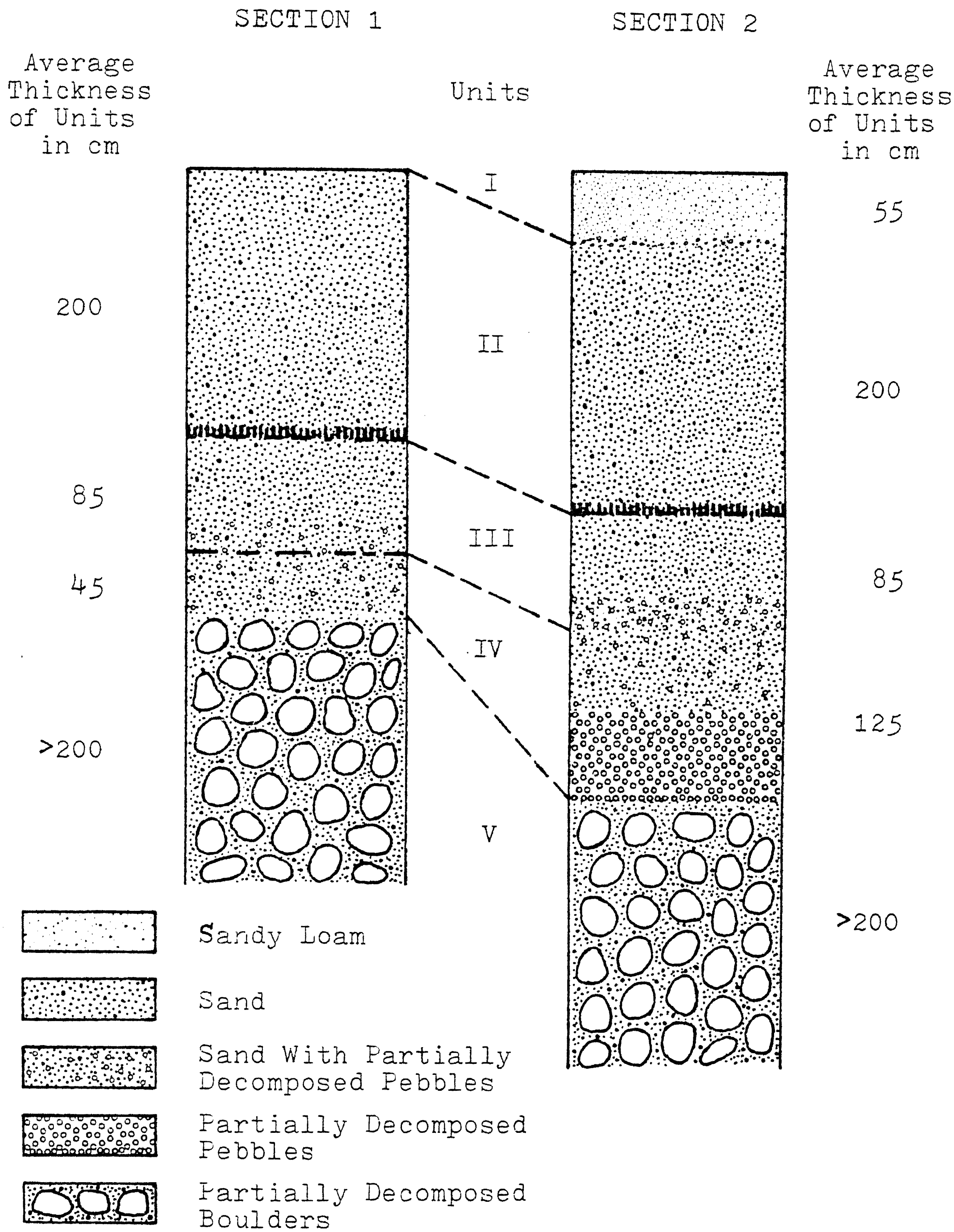


Fig. 34.--Stratigraphy of sections east of Ciudad Quesada along the road that leads to La Marina.

pebbles up to 1.5 cm in diameter which vary in thickness from a single line to a maximally 12.5 cm wide zone. Near the top of the unit, a wavy, discontinuous, thin zone of iron and manganese dioxide concretions designates the lower boundary of the plow layer.

Unit II, which underlies Unit I in Section 2 and constitutes the surface unit in Section 1, is about 2 m thick in both sections. It has a sandy texture and dark yellowish brown color (10YR 3/4) which changes to dark brown (10YR 3/3) farther down in the unit. The bottom of the unit is marked by a thin, discontinuous layer of manganese dioxide concretions which adjoins an overlying discontinuous, 5 to 7 cm wide, yellowish brown layer of small columnar aggregates of loamy sand.

Unit III, which underlies Unit II in both sections, varies in thickness from 75 to 90 cm. The upper 60 cm of the unit are sandy in texture and change in color from dark brown (10YR 3/3) in the upper to dark yellowish brown (10YR 3/4) in the lower part in both sections. The lower 15 to 30 cm of the unit also are sandy in texture, but differ in other properties among the two sections. In Section 1, the lower part of Unit III is dark yellowish brown (10YR 3/4) in color, occasionally contains small, partially decomposed pebbles, and terminates in a thin, discontinuous, gray layer. In Section 2, the lower part of Unit III is brown to dark brown (7.5YR 4/4) in color with numerous red and yellow mottles, contains a relatively large number of small, partially decomposed pebbles, and lacks the thin, discontinuous, gray layer which occurs at the bottom of this layer in Section 1.

Unit IV, the next lower unit in both sections, differs the most among the two sections. In Section 2, the total thickness of Unit IV is 1.25 m. The upper 65 cm of the unit are sandy in texture, contain small, partially decomposed pebbles, and change in color from dark yellowish brown (10YR 3/4) in the upper 35 cm to brown to dark brown (10YR 4/3) in the lower 30 cm. The lower 60 cm of the unit consist entirely of small, decomposed pebbles, change in color from reddish brown (5YR 4/4) in the upper to yellowish brown (10YR 5/4; 5/6) in the lower part, contain numerous red and yellow mottles throughout, and terminate in a layer of indurated, partially decomposed, small pebbles. In Section 1, Unit IV is only 45 cm thick and closely resembles the upper 35 cm of Unit IV in Section 2.

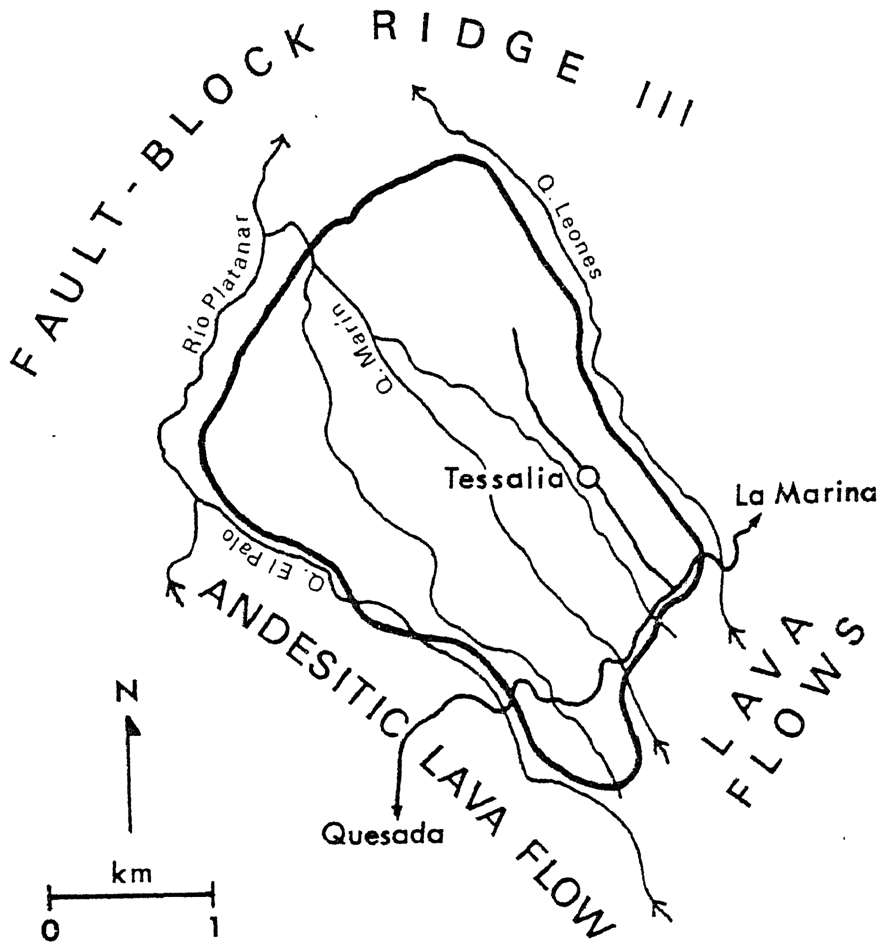
Unit V, the lowermost unit in both sections, consists of large, partially decomposed boulders which are embedded in a dark brown (7.5YR 4/4) to dark yellowish brown (10YR 3.5/4) finer matrix. In Section 2, 2 m of the unit were exposed near the bottom of the exposure. However, the total thickness of this unit could not be determined.

The same stratigraphic sequence as the one described above in detail for the central portion of the Quesada fan, was also observed on the westcentral and lower western portions of the fan in several exposures along the road that leads northward from the center of Ciudad Quesada to the village of Florencia. On the eastcentral portion of the fan, only Unit III, forming the surface of the fan, and Unit IV were recognized, indicating that this portion of the fan experienced fewer episodes of deposition than the remainder of the fan. The upper four depositional units (Units I to IV) on the Quesada fan are interpreted as consisting of alluvium which most likely was derived from the surfaces of the lava flows south of the fan. The next lower unit (Unit V) is believed to be of laharic origin.

Tessalia Alluvial/Laharic Fan

The Tessalia fan, located in the southcentral part of the Piedmont Province of southern San Carlos northeast of the Quesada fan (Fig. 19), was built up by the Quebrada Marín and its tributaries, which originate on the surface and at the base of lava flows that bound the fan in the south. The sides of the fan are delineated by the Quebrada Leones in the east and by the Quebrada El Palo in the west. In the north, the distal end of the fan rest against the backslope of tilted fault-block ridge III (Fig. 35).

Although the Tessalia fan has a similar location as the Quesada fan, being located between lava flows in the south and tilted fault-block ridge III in the north, the surface deposits on this fan have a finer texture than those on the Quesada fan. With the exception of the upper 20 cm, which have a sandy loam to clay loam texture, the upper 2 m of the deposits consist of clay. Colors within



Approximate Fan Boundary

Streams Roads O Settlements

Fig. 35.--Tessalia alluvial/laharic fan.

this distance change from dark yellowish brown (10YR 3/4) to reddish brown (5YR 4/4) on the upper portion of the fan, and from dark brown to brown (7.5YR 4/4) to yellowish red (5YR 4/6) on the lower portion of the fan. The fine-textured surface deposits are underlain by large boulders of suggested laharic origin, as evidenced in an exposure near the distal end of the fan.

Alluvial Plains

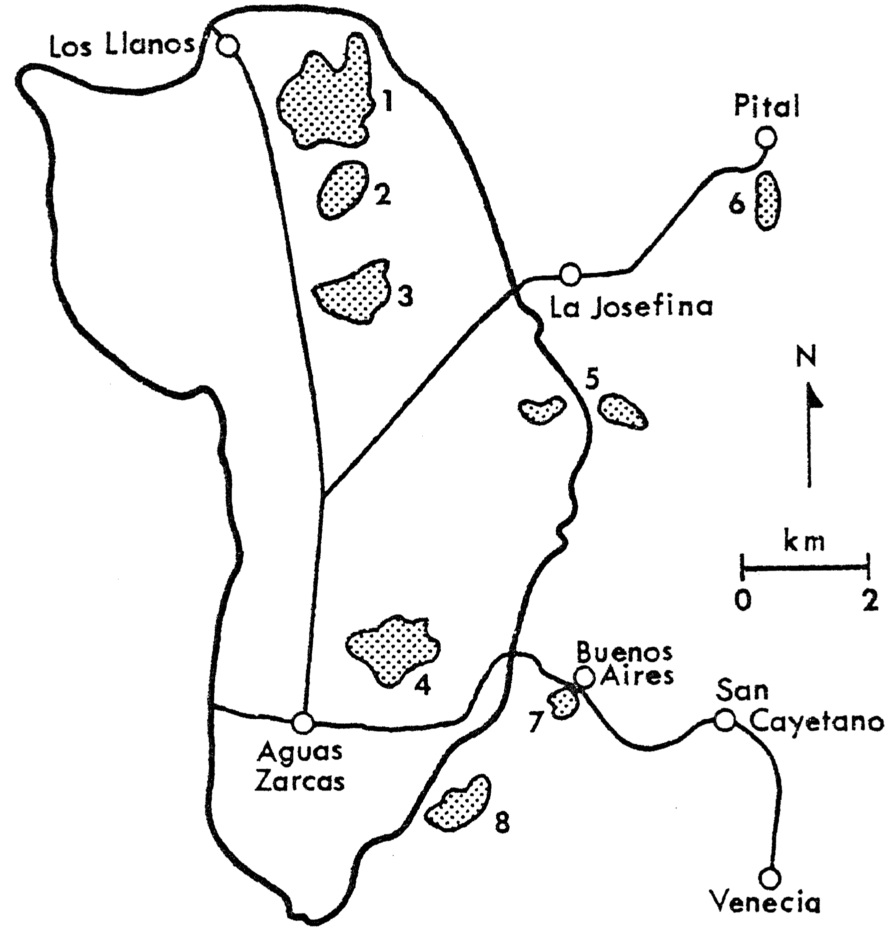
In the northcentral part of the Piedmont Province of southern San Carlos, two small alluvial plains are present between the front scarp of tilted fault-block ridge II and the backslope of tilted fault-block ridge I (Fig. 19). They were created by the Río Platanar and the Río San Rafael, probably during and shortly after the formation of tilted fault-block ridges, at a time when these antecedent streams incised their channels in the upstream reaches and consequently carried an increased load of sediments. The surfaces of the alluvial plains are extremely flat, contrasting sharply with the adjacent slopes of the tectonic landforms.

The alluvial plain which was built up by the Río Platanar extends westward from the point where the stream emerges from tilted fault-block ridge II to the Quebrada Azul, a tributary which enters the stream from the south. It is 4 km long and gradually widens from slightly over 100 m in the east to slightly over 1 km in the west. The alluvial plain which was formed by the Río San Rafael extends from south of the village of San Francisco in the east to the Quebrada Muerta in the west. It is 4.5 km in length and varies in width from 0.5 km at the village of San Rafael to maximally 1.5 km in its eastcentral portion.

Cinder Cones and Associated Pyroclastic Deposits

In the eastcentral and eastern parts of the Piedmont Province of southern San Carlos, several cinder cones are present. Five cinder cones are located on the Aguas Zarcas fan; four occur east of the fan (Fig. 36). Three of the cinder cones, located on the lower portion of the Aguas Zarcas fan, and a fourth, located on the upper portion of the fan, appear to be aligned along an extension of the north-south fault that created the immense fault scarp north of the summit area of Volcán Viejo in the Mountainous Province of San Carlos (p. 31). For the other cinder cones no definite alignments along faults are recognizable.

The three cinder cones which are located on the lower portion of the Aguas Zarcas fan, including Cerro Los Chiles and Lomas Hermosa and Kopper, two previously unnamed cinder cones (Fig. 36), rise abruptly from the gently sloping fan surface to elevations of 250 m, 215 m, and 290 m, respectively. The relative relief on the northwestern, downslope-facing sides of the cinder cones is 130 m on Cerro Los Chiles and Loma Kopper and 75 m on Loma Hermosa, the smallest of the three cinder cones. On the southern, upslope-facing sides of the cinder cones, the relative relief is about 20 m less than on their northwestern sides. A quarry, located on the west side of Cerro Los Chiles, provided information about the nature and stratigraphy of pyroclastic deposits composing this cinder cones (Fig. 37). As displayed in the quarry face, the cinder cone consists



CINDER CONES

1 Cerro Los Chiles
2 Loma Hermosa
3 Loma Kopper
4 Loma Juan Murillo
5 Lomas Barrantes
6 Loma Pital
7 Loma Buenos Aires
8 Loma Morera

——— Roads
O Settlements
——— Boundary of Aguas Zarcas Fan

Fig. 36.--Spatial distribution of cinder cones and associated pyroclastic deposits in the eastcentral and eastern portions of the Piedmont Province of southern San Carlos. The pyroclastic deposits occur east of the Aguas Zarcas fan. They were studied between the villages of Buenos Aires and Venecia in the southern part and between the villages of La Josefina and Pital in the northern part of this area.

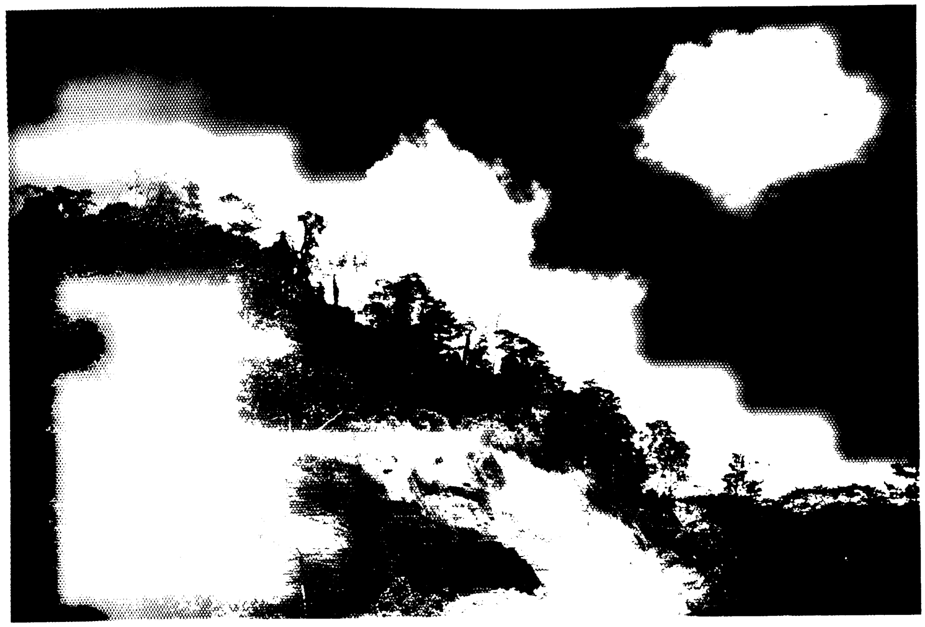


Fig. 37.--Quarry on the west side of Cerro Los Chiles in 1968. Staining of the quarry face and the presence of vegetation indicate that the quarry had been inactive for several years. Note that the pyroclastic deposits which compose the cinder cone are relatively fine textured and thinly bedded, best seen in the lower center above the dark spot, which is a shadow cast by the ceiling of a small cavity dug into the quarry face. Also note that the pyroclastic deposits are weathered to great depth, as indicated by a yellow brown color. The reddish brown color at the top of the exposure marks the zone of soil formation.

of thinly bedded, relatively fine-textured pyroclastic deposits. They are weathered to great depth, as indicated by a yellow brown color of subsurface deposits.

Loma Juan Murillo, the cinder cone which is located on the upper portion of the Aguas Zarcas fan, rises to 518 m (Fig. 36). Although the elevation of this cinder cone is substantially higher than that of the other cinder cones on the Aguas Zarcas fan, the relative relief between the fan surface and the summit of Loma Juan Murillo is comparable to that reported for the two larger cinder cones on the lower portion of the fan. This may suggest that the cinder cones on the Aguas Zarcas fan rest upon a sloping, pre-volcanic surface. Alternatively, the true size of Loma Juan Murillo may be hidden because of partial burial by fan deposits.

The fifth cinder cone on the Aguas Zarcas fan, Loma Barrantes, is located at the eastcentral margin of the fan about 2 km south of the village of La Josefina. Immediately to the east of this cinder cone beyond the margin of the fan another, previously unreported cinder cone is present. The summit elevation of this cinder cone is slightly lower than that of Loma Barrantes, which rises to 290 m. The two cinder cones are referred to collectively as Lomas Barrantes (Fig. 36).

Another previously unreported cinder cone, named Loma Pital, is located at the southern outskirts of the village of Pital (Fig. 36). The cinder cone rises to an elevation of 240 m, as determined with the aid of an Abney level. The relative relief between the summit of the cinder cone and the surrounding flat terrain is 80 m.

The remaining two cinder cones occur east of the upper portion of the Aguas Zarcas fan (Fig. 36). Loma Morera, which rises to an elevation of 621 m, is located immediately east of the margin of the fan about 2.5 km southeast of the village of Aguas Zarcas. The relative relief between the fan surface and the summit of the cinder cone is 100 m. Loma Buenos Aires, a previously unnamed cinder cone, is located about 2.5 km northeast of Loma Morera south of the village of Buenos Aires. Although the summit of the cinder cone has an elevation of 461 m, it rises only 60 m above the surrounding terrain.

Volcanic activity in the eastern part of the Piedmont Province of southern San Carlos has been intermittent, as evidenced by the presence of several superimposed pyroclastic units in the area east of the Aguas Zarcas fan. Preliminary studies of the differing deposits were undertaken between the villages of Buenos Aires and Venecia in the southern part and between the villages of La Josefina and Pital in the northern part of this area (Fig. 36).

In the southeastern part of the Piedmont Province of southern San Carlos, four different pyroclastic units are recognizable. The three lower units, overlying extremely weathered laharic and/or blocky lava deposits, extend between the eastern margin of the Aguas Zarcas fan and the village of San Cayetano. The uppermost pyroclastic unit is present in all but the westernmost part of this area, starting to occur at the eastern edge of the village of Buenos Aires. In contrast to the three lower pyroclastic units, the surface pyroclastic unit extends beyond San Cayetano to Venecia, overlying alluvial deposits between these two villages. The thickness of this unit varies between 50 and 100 cm, being greatest where laid down in former depressions. It shows a much lower degree of weathering than the three lower pyroclastic units and can be traced by an almost continuous, light gray, up to 30 cm wide zone of relatively unweathered volcanic ash at its base (Fig. 38).

Fig. 38--Pyroclastic deposits in the southeastern part of the Piedmont Province of southern San Carlos about midway between the villages of Buenos Aires and San Cayetano along a side road that leads to the village of La Unión. Note the undulating, light gray zone of relatively unweathered volcanic ash at the level of the pick, which marks the lower boundary of the uppermost pyroclastic unit.

In the northeastern part of the Piedmont Province of southern San Carlos, the number of pyroclastic units decreases from west to east, as the thickness of the surface unit increases. In the western part of this area, extending from the eastern margin of the Aguas Zarcas fan to approximately 700 m east of the village of La Josefina, three pyroclastic units are present. East of the bridge that crosses the Río Tres Amigos at La Josefina, the thickness of the surface unit is about 2 m; that of the two underlying units varies from 1.5 to 2 m, and from 1 to 1.5 m, respectively. In the central part of this area, only two pyroclastic units are recognizable. The surface unit has an average thickness of 3 m and is marked at the base by a discontinuous, yellow, between 20 and 60 cm wide zone of small to medium pyroclastic fragments which are cemented by iron oxides and manganes dioxide. The underlying unit is exposed for 4.5 to 5 m above the bed of the road that leads to the village of Pital. In the eastern part of this area, only one massive, over 10 m thick, pyroclastic unit seems to be present, as displayed in exposures along the new road at the west entrance of Pital.

Because of the fragmentary knowledge about the spatial distribution of individual pyroclastic units and a lack of recorded data on prevailing wind directions, it seems futile to speculate on respective source areas for the various pyroclastic deposits which are present in the area east of the Aguas Zarcas fan. Numerous, detailed stratigraphic studies on and between cinder cones are required in order to determine the origin of these deposits. Possible influx of pyroclastic materials from outside the study area also needs to be considered.

Spatial and Temporal Relationships Between Major Landform Types in Southern San Carlos

In southern San Carlos, landforms of different origins show a distinct spatial segregation. This is true especially for landforms in the Piedmont Province of the study area, where tectonic, alluvial/laharic, and volcanic landforms dominate different parts of the landscape. In the northwestern, northcentral, and central parts of this area, three tilted fault-block ridges are the most prominent landforms. In the southwestern, southcentral, and eastcentral parts of the area, alluvial/laharic fans are of greatest importance. In the eastern part of the area, cinder cones and associated pyroclastic deposits are predominant. Exceptions to this general pattern are found in the northcentral part of the area, where two small alluvial plains extend between tilted fault-block ridges I and II, and in the eastcentral part of the area, where several cinder cones rise above the surface of the Aguas Zarcas fan (Fig. 11).

In the Atlantic Lowland Province of southern San Carlos, landforms of different origins are spatially less segregated than in the Piedmont Province of the study area. In fact, small hills of laharic origin and alluvial plains show a nearly ubiquitous distribution, coexisting throughout most of the area. Paired terraces are spatially more segregated in that they are restricted to the vicinity of present-day stream courses.

In a geographic region, relative ages of landforms can be inferred from their spatial distribution only if individual landforms are not segregated in space. In southern San Carlos, where spatial segregation of landforms according to origin is apparent, relative ages of landforms cannot be assessed for the region as a whole. On the other hand, relative ages can be determined for landforms in different parts of the study area.

In the Atlantic Lowland Province of southern San Carlos, small hills of laharic origin are the oldest and low-level paired terraces the youngest landforms. Alluvial plains are intermediate in age between these two landforms. Small hills of laharic origin are older than surrounding alluvial plains because they invariably rise to higher elevations and show a greater degree of weathering than the alluvial landforms. Paired terraces are youngest among the three landforms because they occur at and below the level of alluvial plains adjacent to present-day stream courses.

In the Piedmont Province of southern San Carlos, age relationships between landforms are clearest in the western and central parts of the area. Tilted fault-block ridges are older than both alluvial/laharic fans and alluvial plains because, with the exception of the easternmost fan, alluvial/laharic fans built up against the backslope of tilted fault-block ridges and alluvial plains formed between the front scarp and backslope of two of the tectonic landforms. Age distinction between individual alluvial/laharic fans and between alluvial/laharic fans and alluvial plains, especially regarding surface deposits, cannot be made because the position of these landforms in relation to tilted fault-block ridges only provides an estimate of their initial ages.

The five cinder cones in the eastcentral part of the Piedmont Province of southern San Carlos are older than surrounding surface deposits on the Aguas Zarcas alluvial/laharic fan because pyroclastic deposits do not extend beyond the cinder cones onto the surface of the fan. Moreover, because of their tectonic alignment the four westernmost of these cinder cones probably have similar ages. Age relationships between these and other cinder cones in the Piedmont Province of southern San Carlos are indeterminable because of the disjunct spatial distribution of these landforms. Age relationships between individual cinder cones in the eastern part of the Piedmont Province also are uncertain because available data on the spatial distribution of differing pyroclastic deposits, extending between cinder cones, are insufficient to ascertain their respective source areas. The fact that different pyroclastic units are present in this area may indicate that the cinder cones have dissimilar ages. Age relationships between the cinder cones in the eastern part of the Piedmont Province and alluvial/laharic landforms, as well as age relationships between all cinder cones in the Piedmont Province and tilted fault-block ridges cannot be determined because of the distinct spatial segregation of the two differing landform types within the Piedmont Province of southern San Carlos.

Laharic landforms in the Atlantic Lowland Province of southern San Carlos antedate tectonic, alluvial/laharic, and alluvial landforms in the Piedmont Province of the study area. Small hills of laharic origin must be older than tilted fault-block ridges because widespread laharic deposition throughout the Atlantic Lowland Province seems possible only before tilted fault-block ridges provided barriers for the descent of massive lahars. They also are older than alluvial/laharic fans and alluvial plains because these landforms are younger than the tectonic landforms.

Alluvial plains in the Atlantic Lowland Province of southern San Carlos were created both during and after the formation of tilted fault-block ridges in the Piedmont Province of the study area, when streams in the Atlantic Lowland Province carried an increased load of sediments because of accelerated erosion in their upper reaches in response to steepening of stream gradients caused by the tectonic events and the resultant buildup of alluvial/laharic fans. Although the formation of alluvial plains in the Atlantic Lowland Province started during the creation of tilted fault-block ridges, upper portions of these landforms not only are younger than the tectonic landforms but also younger than the upper portions of alluvial/laharic fans in the Piedmont Province of the study area.

Paired terraces along the lowland reach of the Río

Kopper in the Atlantic Lowland Province of southern San Carlos are younger than laharic surface deposits on the eastern portion of the La Marina fan in the southcentral part of the Piedmont Province of the study area, provided that these terraces resulted from stream adjustments of the Río Aguas Zarcas in response to laharic deposition on this fan. Both the paired terraces and the upper portions of alluvial plains in the Atlantic Lowland Province are younger than the cinder cones on the Aguas Zarcas fan in the eastcentral part of the Piedmont Province. On the other hand, age relationships between the cinder cones in the eastern part of the Piedmont Province and landforms in the Atlantic Lowland Province cannot be assessed because of the disjunct spatial distribution of these landforms in the study area.

In summary, on the basis of geomorphic evidence relative ages of some, but not all landforms in southern San Carlos can be determined. The spatial distribution of landforms in the study area permits mainly an assessment of relative ages of adjacent landforms and does not indicate the magnitude of age differences between landforms. In the following chapter, the temporal distribution of modern and buried soils in southern San Carlos is discussed, on the assumption that variations in degree of soil development provide information about age relationships between spatially disjunct landforms and about the magnitude of age differences between landforms in the region.

CHAPTER III

PEDOGENIC EVIDENCE

Introduction

Soils were studied mainly for the purpose of gaining a more complete understanding of the temporal distribution of landforms in southern San Carlos. For this reason, no attempt at systematic soil classification is made, but selected pedogenic properties are used as criteria for distinguishing between soils of different ages.

Field and laboratory methods are described first, followed by a summary of the nature of and variations in soil-forming factors in southern San Carlos. Then, several hypotheses concerning the relationships between selected pedogenic properties and degree of soil development are formulated and brief rationales for them are stated. In the following discussion of the temporal distribution of soils in the study area modern soils and paleosols are treated separately. The chapter concludes with a summary of overall age relationships between soils in southern San Carlos.

Field Methods

Field studies were initiated during a two-week period in the summer of 1968 and completed during a two-month field season in the spring of 1970. They included: (1) selection of sampling sites for extended soil investigations, (2) detailed description of soil profiles and collection of both disturbed and undisturbed soil samples at these sites, and (3) general description of soils and collection of disturbed samples from selected soil horizons in exposures between major sampling sites.

Selection of Sampling Sites

Thirty-four sites were chosen for detailed description and sampling of soil profiles. At these sites, 34 modern and 11 buried soils were studied (Fig. 39). In addition, selected pedogenic properties were determined for soils located between major sampling sites. The following criteria were considered in site selection: (1) areal distribution, (2) accessibility, and (3) vertical extent of exposures.

Detailed description and sampling of soil profiles were undertaken for at least one site on each major landform type in the Atlantic Lowland and Piedmont Provinces of the study area. However, on most landforms more than one major sampling site was chosen in order to assess variations in pedogenic properties which might stem from topographic and/or parent-material differences. For example, major sampling sites on small hills of laharic origin were located in the eastern, central, and western parts of the Atlantic

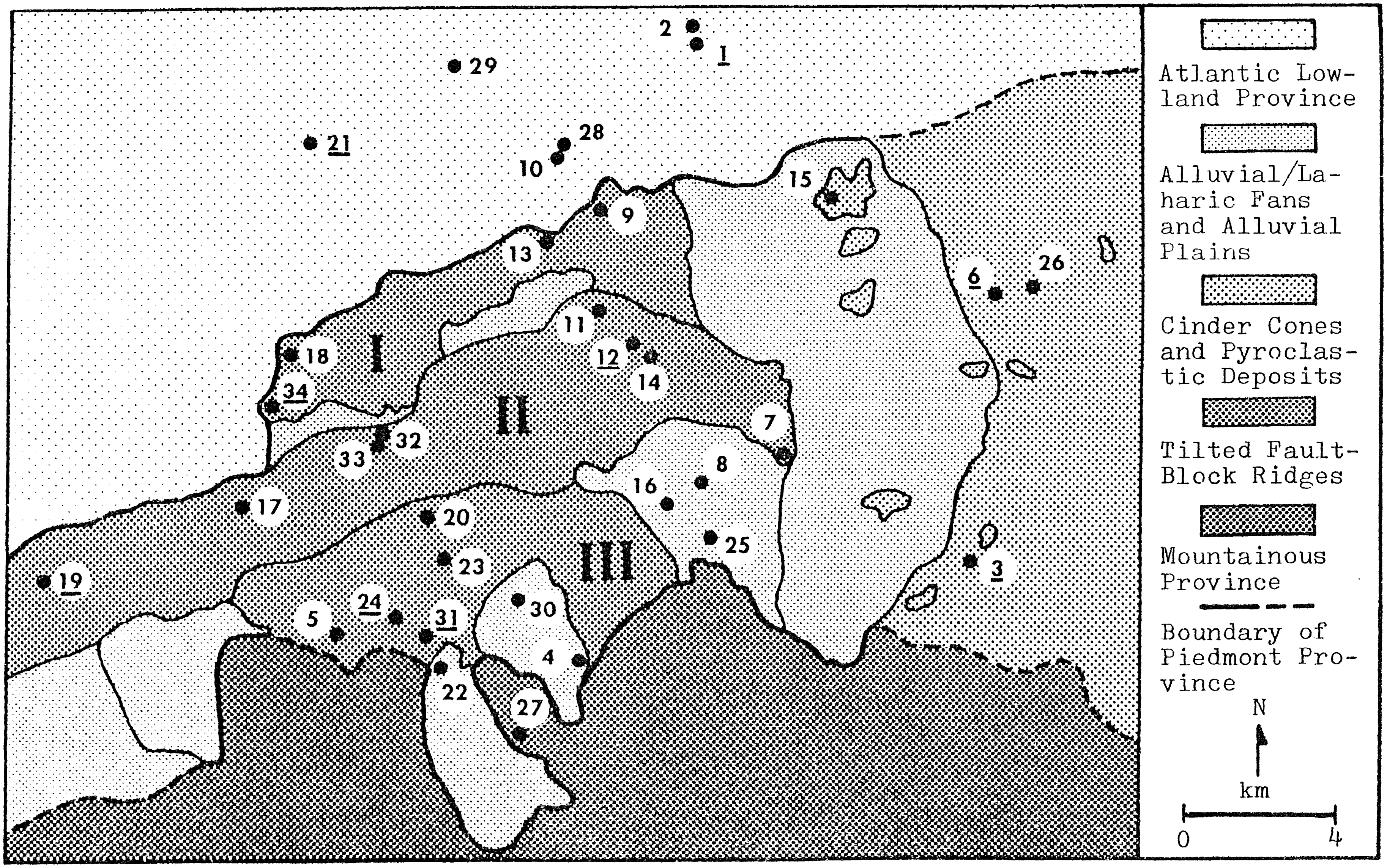


Fig. 39.--Location of major soil sampling sites. Underlined numbers indicate where buried soils are present.

Lowland Province. In the Piedmont Province, major sampling sites were selected on several of the alluvial/laharic fans, on the eastern, central, and western portions of tilted fault-block ridges, and at several localities on cinder cones and associated pyroclastic deposits (Fig. 39).

Most sites were located along major roads. They were chosen for accessibility and relatively large vertical extent of exposures. At these sites, both modern and buried soils were studied. Some sites were located along secondary roads and a few along stream banks. At these shallow exposures, investigations were generally restricted to modern soils.

Description and Sampling of Soil Profiles

Since all sites were located in preexisting man-made or natural cuts, care was taken in cleaning soil profiles. Depending upon the apparent degree of subaerial weathering, between 10 and 30 cm of exposed surfaces were removed before description and sampling of soil profiles were undertaken.

After identification of individual soil horizons, the following pedogenic properties were determined at major sampling sites: horizon thickness; nature of lower horizon boundary; color (with the aid of Munsell soil color charts); texture (by feel); structure; consistence when moist, a measurement of soil firmness, and when wet, a measurement of soil stickiness and plasticity (by feel); pH (colorimetrically by use of a field testing kit); and the presence and abundance of roots, soil organisms, argillans or silicate clay skins, mottles, and concretions. In soils which were studied between major sampling sites not all of these pedogenic properties were recorded systematically. During the spring of 1970, pH determinations and texture estimates by feel were no longer performed in the field, since it was found that laboratory analyses of these pedogenic properties gave more reliable results. On the average, pH determinations by glass electrode were more consistent than those obtained colorimetrically. Moreover, particle-size analyses by the pipette method invariably yielded finer textures than those obtained in the field because clay particles tended to remain in the form of larger aggregates which felt like fine sand when soil was kneaded with water to estimate texture. Detailed field descriptions of soil profiles at the 34 major sampling sites are provided in Appendix I.

Two kinds of soil samples were collected: (1) disturbed samples of about 750 grams each for various laboratory analyses; and (2) undisturbed core samples of equal volume for determinations of moisture content and bulk density (mass or weight of a unit volume of dry soil including both soil solids and pore spaces). Disturbed samples were obtained from each horizon of soil profiles at the 34 major sampling sites and from selected horizons of soils studied between these sites. All disturbed soil samples were air-dried prior to shipment in order to reduce weight. Undisturbed samples were obtained from horizons of

21 soil profiles at major sampling sites. Collection of these samples was discontinued during the second field season because it was found that moisture content and bulk density were very similar for most soils. All undisturbed soil samples were carefully sealed in plastic bags immediately after collection in order to prevent moisture loss during storage and transport.

Laboratory Methods

Several laboratory analyses were performed in order to supplement the field data. The following pedogenic properties were determined: particle-size distribution by the pipette method (Kilmer and Alexander, 1949, p. 15-24); free iron-oxide content by the dithionate method (Olson, 1965, p. 971-972); pH on 1:2.5 suspension by glass electrode (Peech, 1965, p. 920-923); aggregate stability as determined by the index of structure (Sombroek, 1966, p. 122; Harris, 1971, p. 156); moisture content by gravimetry with oven drying (Gardner, 1965, p. 92-93); and bulk density by the core method (Blake, 1965, p. 375-377). For definitions and procedures of laboratory analyses see Appendix II. Results of laboratory analyses for the 34 soil profiles at major sampling sites are presented in Appendix III.

Soil-Forming Factors in Study Area

As generally recognized, there are five major factors that control the formation of soils. They are: (1) regional climate, particularly precipitation and temperature; (2) organisms, especially the natural vegetation; (3) nature of the parent material, including texture, structure, and mineralogical composition; (4) topography, including direction and steepness of slope and the position of the water table; and (5) time, elapsed since a parent material was subjected to soil formation (e.g. Jenny, 1941). Soil-forming factors in the study area are treated below. Since the nature of and variations in these factors have already been described in some detail in various parts of the two preceding chapters of the dissertation, only the most relevant facts are summarized.

Regional Climate

At present, the climate of southern San Carlos is characterized by large annual precipitation totals and high mean monthly temperatures. Although both seasonal and regional variations in precipitation and temperature are evident, the entire region experiences a humid tropical (Af) climate (Chapter I, p. 8-15). In the past, the climate of the area appears to have differed only slightly from that of today, having been somewhat cooler and equally as wet as, or possibly somewhat wetter than, at present (Chapter I, p. 16-18). The described climatic characteristics imply that southern San Carlos has experienced a relatively uniform and constant climate throughout the existence of the area.

Natural Vegetation

Both the existing and the past natural vegetation in southern San Carlos have consisted of forest, ranging from predominantly tropical forest types to subtropical rain-forest (Chapter I, p. 18-20). Although differing in floristic composition, the various forest types native to the area are similar in physiognomy. The most important common trait is a multi-layered canopy, a feature which has had two significant effects throughout the region. These are: (1) creation of a microclimatic environment in which already small macroclimatic variations in precipitation and temperature were further diminished; and (2) prevention of excessive erosion by reducing the impact of rain through interception and dispersion of the falling precipitation (Chapter I, p. 21).

Parent Material

The parent materials in southern San Carlos consist mainly of alluvial, laharic, and pyroclastic deposits of predominantly andesitic composition (Chapter I, p. 6-7). Because of the unconsolidated nature of these deposits, knowledge of the original texture of the differing parent materials would especially be desirable. Unfortunately, relatively little information about variations in this parent-material property is available because deep subaerial weathering and/or lack of large vertical exposures hampered the examination of unaltered parent materials. Nevertheless, the following statements can be made: (1) Of the three principal parent materials, only laharic deposits contain a high proportion of coarse rock fragments. On the other hand, characteristic for these deposits is a moderately fine-textured to fine-textured matrix relatively high in clay. (2) Three of five alluvial parent materials have a sandy loam or moderately coarse texture. One alluvial parent material is a loamy sand or coarse in texture; another is a clay loam or moderately fine in texture. Considering that all but one of the alluvial parent materials for which the original texture is known contain a relatively high proportion of sand and a relatively small proportion of clay, alluvial parent materials in general probably are characterized by coarse to moderately coarse textures. (3) The original texture of pyroclastic parent materials, although ranging widely from moderately coarse to fine, is characterized by a relatively high proportion of silt. In each of five pyroclastic surface deposits, ranging in original texture from sandy loam to clay loam, the percentage of silt is greater than or equals the percentage of clay. In two of three pyroclastic subsurface deposits, ranging in original texture from clay loam to clay, the percentage of silt is greater than the percentage of sand.

Topography

The topography in southern San Carlos is characterized by a general increase in elevation from north to south and a substantially greater local relief in the piedmont than in the Atlantic Lowland part of the region (Chapter II, p. 27, 40). Of the three main topographic variables, differences in slope orientation are considered to be of minor importance because of the low-latitude geographic location of the area. The position of the water table generally is well below landform surfaces in the piedmont part of the region; in the Atlantic Lowland part of the area, a fluctuating water table normally extends into the zone of soil formation. Greatest topographic variations in the region exist with regard to steepness of slopes, which range from less than 1° to nearly 90°. On the other hand, at soil sampling sites slope angles do not exceed 14° so that variations in this topographic variable are reduced to some extent.

Time

All parent materials in southern San Carlos are believed to date from the Quaternary Period (Chapter I, p. 6). Moreover, geologic and geomorphic evidence suggest that parent materials were laid down at different times within this period (Chapter I, p. 7; Chapter II, p. 90-94). However, because of the scarcity and indeterminate nature of radiocarbon dates, information about absolute ages of differing parent materials is not available (Chapter I, p. 8).

Pedogenic Properties and Relative Soil Age in Study Area

In a given geographic region, degree of soil development can be used as a qualitative measure of soil age, provided that the major soil-forming factors other than time can be considered constant (Birkeland, 1974, p. 23). Constancy of a factor can be assumed, if (1) variations in the factor are small and (2) variations in the factor, although large, have no important effect on soil formation (Birkeland, 1974, p. 126). As shown in the preceding section, in southern San Carlos two of the four soil-forming factors in question, including the regional climate and the natural vegetation, show relatively small variations and therefore can be considered constant. On the other hand, variations in parent materials and topography are sufficiently large so that some influence on pedogenesis cannot be excluded. Variations in parent materials are believed to have been influential primarily at the onset of soil formation but to have lost in importance with the passage of time because of the extremely rapid rate of weathering in the hot and humid climate of the study area. Topographic variations probably account for some differences in pedogenic properties but in general are considered to be less important than variations in time, elapsed since different parent materials were subjected to soil formation.

In order to determine degree of soil development as a function of time, pedogenic properties have to be chosen that require a long time to form (Birkeland, 1974,

p. 163-164). In this study, soil texture, silt/clay ratios, illuvial-clay content, soil color, and free iron-oxide content are investigated. Relative ages of soils are determined by ranking them on the basis of differences in these diagnostic properties. As an aid, hypotheses concerning the relationships between the selected pedogenic properties and degree of soil development are formulated to be used as guidelines in the discussion of the temporal distribution of soils in southern San Carlos. The hypotheses and brief rationales for them are stated below.

Hypothesis 1

<u>Soil texture becomes finer with increasing degree of soil development</u>.

Despite greater intensity of pedogenic weathering than in other geographic regions, differences in soil texture are evident in soils of the humid tropics. Soils at an early stage of development generally display relatively coarse textures throughout the solum (upper, genetically formed part of soils, including the A and B horizons in normal soils). As pedogenic weathering proceeds, soil textures become rapidly finer, especially in subsoil horizons, where <u>in situ</u> clay production is augmented by clay illuviation (precipitation of translocated clay derived from the upper part of soils). For this reason, soils at an intermediate stage of development possess notably finer textures in subsoil than in surface horizons. On the other hand, soils at an advanced stage of development are characterized by greater similarity in epipedon (upper part of soils darkened by organic matter and/or having experienced eluviation or removal of soil constituents) and subsoil textures because, in time, translocation of clay decreases in importance relative to _in situ_ clay formation (Birkeland, 1974, p. 112-113).

Hypothesis 2

Silt/clay ratios in soils decrease with increasing degree of soil development.

Silt/clay ratios have been found to be very useful for making age distinctions between soils in the humid tropics. For example, Sombroek (1966, p. 72) used a silt/clay ratio of maximally 0.25 in subsoil horizons as one of the criteria for separating latosols from latosolic podzolic soils in the Amazon region of South America. D'Hoore (1960, p. 17) proposed the same value as the upper limit for African latosols formed on alluvium and sedimentary rocks and a ratio of 0.15 for those formed on metamorphic and igneous rocks. Van Wambeke (1962, p. 128) reports that a silt/clay ratio of 0.15 is the critical value for the distinction between Tertiary and Quaternary soil parent materials derived from a great variety of rock types in the Congo Basin of Central Africa. In the present study, a progressive decrease in silt/clay ratios is expected to occur with increasing degree of soil development in both epipedons and subsoil horizons because, as soil texture becomes finer, silt content decreases and clay content increases in both soil horizons. However, silt/clay ratios are predicted to be lower in subsoil than in soil-surface horizons because of more rapid changes in respective particle-size fragments in the lower part of soil sola.

Hypothesis 3

Argillans in subsoil horizons are most pronounced in soils at an intermediate stage of soil development.

As in other geographic regions, in the humid tropics argillans tend to be absent from soils at an early stage of development because clay formation and transfer are relatively slow processes (Birkeland, 1974, p. 164). On the other hand, as pedogenic weathering proceeds, the formation and translocation of clay advance rapidly, resulting in numerous, well-developed argillans in subsoil horizons of soils at an intermediate stage of development. Soils at an advanced stage of development generally show a lower degree of clay illuviation than soils at an intermediate stage of development because destruction and incorporation of argillans into the subsoil matrix tend to occur as clay content increases (Birkeland, 1974, p. 108, 112). Moreover, translocation of clay is limited in these soils, apparently due to the mutual attraction of oppositely charged 1:1 lattice clays (predominantly kaolinite) and sesquioxides (iron and aluminum oxides), which are the main constituents in tropical soils at an advanced stage of development (Birkeland, 1974, p. 114; Soil Survey Staff, 1960, p. 53).

Hypothesis 4

Soil color becomes redder with increasing degree of soil development.

In many geographic regions, older soils are redder than younger soils, even if they have formed on different parent materials (Birkeland, 1974, p. 167; Buckman and Brady, 1969, p. 332). Degree of soil redness generally is related to the relative abundance of iron oxides and hydroxides (oxides containing associated water molecules), which form during pedogenic weathering. Although in the humid tropics most soils have yellow to red colors because of the rapid breakdown of iron-bearing minerals, color hues (dominant spectral colors) in well-drained tropical soils are expected to become redder with increasing degree of soil development. Moreover, since differences in the amount of iron oxides and hydroxides between epipedons and subsoil horizons tend to increase with increasing degree of soil development (Hypothesis 5), older soils are predicted to show greater differences in color hues between epipedons and subsoil horizons and to exhibit stronger subsoil chromas (greater purity of spectral colors) than younger soils.

Hypothesis 5

Free iron-oxide content in soils increases with increasing degree of soil development.

Although in the humid tropics a large proportion of iron oxides combine with water to form hydrous-oxide clays (Buckman and Brady, 1969, p. 89), free iron oxides are abundant in most soils. The formation of iron oxides in soils results from the breakdown of iron-bearing minerals during pedogenic weathering. Therefore, the free iron-oxide content of soils is expected to increase with increasing degree of soil development. Moreover, percentages of free iron oxides are predicted to be higher in subsoil than in soil-surface horizons because of translocation of free iron oxides from upper to lower parts of soil sola (Birkeland, 1974, p. 105-106).

Discussion

As explained in the following discussion of the temporal distribution of soils in southern San Carlos, silt/clay ratios and soil texture are most useful for the determination of relative ages of soils in the study area. Free iron-oxide content, soil color, and illuvial-clay content have more limited value in that they serve to differentiate only between soils of widely different ages. Relationships between pedogenic properties and relative soil age are generally clearer in modern than in buried soils. The temporal distribution of modern soils and of paleosols are treated separately, each according to the hypothesized relationships between selected pedogenic properties and degree of soil development.

Modern Soils

On the basis of differences in the five pedogenic properties investigated in this study, modern soils in southern San Carlos can be divided into seven soil groups. Two soil groups occur in the Atlantic Lowland Province of the study area, including soils on alluvial plains and soils on small hills of laharic origin. The five remaining soil groups are found in the Piedmont Province of the study area. They include soils on alluvial/laharic fans in the southcentral part, soils on tilted fault-block ridges in the northwestern, northcentral, and central parts, and soils on three different pyroclastic parent materials in the southeastern, northeastern, and eastcentral parts of this area. The latter three soil groups are located between the villages of Buenos Aires and Venecia, in the vicinity of La Josefina, and on the cinder cone Cerro Los Chiles, respectively (Fig. 39).

Soil Texture and Relative Soil Ages

Although it is realized that textural differences in parent materials and topography probably had some influence on the texture of modern soils in southern San Carlos, variations in this pedogenic property are most closely related to differences in the duration of soil formation. Time of soil formation is the most important variable for the following reasons: (1) several soils which formed on similar parent materials show distinct differences in soil texture; (2) some soils, although having formed on parent materials with dissimilar textures, have developed similar soil textures; (3) in some cases, soils which formed on coarser-textured parent materials have developed finer soil textures than soils which formed on finer-textured parent materials; (4) soils on tilted fault-block ridges, which display the greatest variation in topographic position among soils in the study area, have developed similar soil textures.

On the basis of differences in soil texture, seven groups of modern soils can be distinguished in southern San Carlos. Textural characteristics imply that two are at an early stage, three are at an intermediate stage, and two are at an advanced stage of soil development (Hypothesis 1). Moreover, individual soil groups can be ranked within these broad age categories.

Soil texture is described in three ways. In addition to the use of basic soil textural classes (Soil Survey Staff, 1951, p. 207-211), general soil textural classes are are employed, following two different systems in which soils are grouped in relation to basic soil textural classes into five and four general classes, respectively. The first system distinguishes between coarse-textured, moderately coarse-textured, medium-textured, moderately fine-textured, and fine-textured soils (Soil Survey Staff, 1951, p. 213). The second system makes a distinction between coarse loamy, fine loamy, clayey, and fine clayey soils (Buol, Hole, and McCracken, 1973, p. 27).

The two soil groups which are considered to be at an early stage of soil development occur on the cinder cone Loma Buenos Aires, extending eastward to the village of Venecia, in the southeastern part of the Piedmont Province of southern San Carlos and on the alluvial plains in the Atlantic Lowland Province of the study area. Both soil groups have moderately coarse textures throughout soil sola, having sandy loam textures in both epipedons and subsoil horizons (Table 4). Despite similarity in soil texture, a distinction between the two soil groups is possible because of differences in clay content. The soils on Loma Buenos Aires are coarse loamy in texture, whereas those on the Atlantic Lowland alluvial plains are fine loamy soils (Table 4). The differences in clay content among the two soil groups are important considering that they developed on parent materials with identical textures, both being sandy loams or moderately coarse or coarse loamy in texture. Thus, although both soil groups are at an early stage of soil development, the soils on the alluvial plains in the Atlantic Lowland Province of southern San Carlos, showing a greater degree of soil development than the soils on Loma Buenos Aires, are older than the soils on pyroclastic deposits in the southeastern part of the Piedmont Province of the study area.

The three soil groups which are considered to be at an intermediate stage of soil development are found on pyroclastic deposits in the vicinity of the village of La Jo-

TABLE 4.--Mean Texture of A and B2 Horizons of Modern Soils in Southern San Carlos

Soil Groups	Sand A	Silt A	Clay A	Textural Classes		Sand B2	Silt B2	Clay B2	Textural Classes	
				Basic[a]	General[b]				Basic	General
Loma Buenos Aires (PP)[c] N = 1	68	21	11	Sandy Loam	mc[d], cl[e]	62	30	8	Sandy Loam	mc, cl
Alluvial Plains (ALP)[f] N = 1	54	27	19	Sandy Loam	mc, fl[g]	57	27	17	Sandy Loam	mc, fl
Alluvial/Laharic Fans (PP) N = 5	52	28	20	Loam	m[h], fl	35	21	44	Clay	f[i], fc[j]
La Josefina (PP) N = 2[k]	35	31	34	Clay Loam	mf[l], fl	27	17	58	Clay	f, fc
Tilted Fault-Block Ridges (PP) N = 17[m]	33	28	39	Clay Loam	mf, fc	19	14	67	Clay	f, vfc[n]
Small Hills of Laharic Origin (ALP) N = 5	32	21	47	Clay	f, fc	16	9	75	Clay	f, vfc
Cerro Los Chiles (PP) N = 1	34	10	56	Clay	f, fc	18	3	79	Clay	f, vfc

[a]Soil Survey Staff, 1951, p. 207-211.

[b]Soil Survey Staff, 1951, p. 213; Buol, Hole, and McCracken, 1973, p. 27.

[c]Piedmont Province.

[d]Moderately coarse-textured soils.

[e]Coarse loamy soils.

[f]Atlantic Lowland Province.

[g]Fine loamy soils.

[h]Medium-textured soils.

[i]Fine-textured soils.

[j]Fine clayey soils.

[k]For A horizon N = 1.

[l]Moderately fine-textured soils.

[m]For A horizon N = 16.

[n]Very fine clayey soils.

sefina in the northeastern part of the Piedmont Province of southern San Carlos and on alluvial/laharic fans and tilted fault-block ridges in the western and central parts of the Piedmont Province of the study area. Compared to the two previously discussed soil groups, they possess notably finer mean textures throughout soil sola (Table 4). More importantly, they also have substantially finer textures in subsoil than in soil-surface horizons, a trait which is characteristic of soils at an intermediate stage of soil development (Hypothesis 1).

Information about the texture of parent materials on which the three soil groups formed is limited to three sites on alluvial/laharic fans, two sites on pyroclastic deposits in the vicinity of La Josefina, and one site on pyroclastic deposits in the western part of tilted fault-block ridge III. It ranges from loamy sand or coarse or coarse loamy to clay loam or moderately fine or fine clayey, in-group variation being of similar magnitude as between-group variation. In contrast, mean soil textures of the three soil groups are distinctly different (Table 4), suggesting that duration of soil formation has been more influential than textural differences in parent materials.

Of the three soil groups, the soils on alluvial/laharic fans have the coarsest mean epipedon texture and, although having the same texture designation in subsoil horizons as the soils near La Josefina, mean subsoil clay content is less than in the latter soils. The soils in the vicinity of La Josefina have a finer mean epipedon texture than the soils on alluvial/laharic fans and a coarser mean epipedon and mean subsoil texture than the soils on tilted fault-block ridges. The soils on tilted fault-block ridges have the finest mean epipedon and mean subsoil textures among the three soil groups (Table 4). Thus, although all three soil groups are at an intermediate stage of soil development, they can be ranked on the basis of differences in mean soil texture. Textural differences imply that the soils on alluvial/laharic fans are the youngest and the soils on tilted fault-block ridges are the oldest among the three soil groups, whereas the soils in the vicinity of La Josefina are intermediate in age between the other two.

The two soil groups which are considered to be at an advanced stage of soil development occur on the small hills of laharic origin in the Atlantic Lowland Province of southern San Carlos and on the cinder cone Cerro Los Chiles, located on the lower portion of the Aguas Zarcas alluvial/laharic fan in the eastcentral part of the Piedmont Province of the study area. Both soil groups have a finer mean epipedon texture than all other modern soils in southern San Carlos. Moreover, although having the same texture designation in subsoil horizons as the soils on tilted fault-block ridges, the oldest soils among the three soil groups considered to be at an intermediate stage of soil development, both soil groups contain a greater amount of subsoil clay than the latter soils. Most importantly, they also show a lesser degree of horizon differentiation with regard to clay content than the soils on tilted fault-block ridges, a trait characteristic of soils at an advanced stage of soil development (Hypothesis 1).

The slightly weathered parent material of the soils on Cerro Los Chiles, collected near the bottom of a quarry face on the western side of the cinder cone, has a silt loam or medium or coarse loamy texture. As in other pyroclastic parent materials in southern San Carlos, silt content is relatively high, although clay content is of similar magnitude as in alluvial parent materials. No information is available about the texture of the laharic parent materials. However, judging from the general knowledge about the texture of lahars, they must have contained a certain proportion of silt and clay in addition to coarse rock fragments. The fact that in the modern soils which formed on the laharic parent materials coarse rock fragments are completely disintegrated and incorporated into the soil matrix indicates prolonged pedogenic weathering.

Differences in soil texture between the two soil groups are small since both have the same texture designation in epipedons and subsoil horizons. On the other hand, in the soils on pyroclastic parent materials mean silt content is lower and mean clay content is higher than in the soils on laharic parent materials (Table 4). For this reason, the soils on the cinder cone Cerro Los Chiles are believed to be slightly older than the soils on small hills of laharic origin in the Atlantic Lowland Province of southern San Carlos, provided that differences in parent materials lost in importance with duration of soil formation.

Silt/Clay Ratios and Relative Soil Ages

The data in the preceding section suggest that relative ages of modern soils in southern San Carlos can be determined on the basis of differences in mean soil texture. Differences in clay content served also as a useful criterion for the distinction between soil groups within three broad categories of soil development. Following other authors who found that the ratio between the silt and clay contents of soils was an accurate indicator of relative soil age in several parts of the humid tropics (Hypothesis 2), silt/clay ratios were computed for the modern soils in southern San Carlos. They proved to be most sensitive among pedogenic properties for interpreting age differences between modern soils in the study area, substantiating previous findings from mean soil-textural evidence on the basis of which seven groups of modern soils can be distinguished in southern San Carlos.

Of the two soil groups which on the basis of mean soil texture are considered to be at an early stage of soil development, the soils on Loma Buenos Aires have the highest mean silt/clay ratios in both epipedons and subsoil horizons of all modern soils in southern San Carlos. The soils on the alluvial plains in the Atlantic Lowland Province of the study area have lower but still relatively high mean silt/clay ratios throughout soil sola. Moreover, in contrast to other modern soils, both soil groups have lower mean silt/clay ratios in epipedons than in subsoil horizons (Table 5). This trait is not uncommon in soils at an early stage of soil development and reflects the persistence of textural characteristics inherited from parent materials because of minimal pedogenic weathering. The very high silt/clay ratios encountered in the two soil groups indicate that they are appreciably younger than other modern soils in southern San Carlos. In the Congo Basin of Central Africa, such high silt/clay ratios indicate a Recent age of soil parent materials (Van Wambeke, 1962, p. 128). The data also show more clearly than did differences in mean soil texture that the soils on the cinder cone Loma Buenos Aires are younger than the soils on the alluvial plains in the Atlantic Lowland Province of the study area.

The three soil groups which on the basis of mean soil texture are considered to be at an intermediate stage of soil development have substantially lower mean silt/clay ratios, especially in subsoil horizons, than the two soil groups at an early stage of soil development (Table 5). In the Congo Basin of Central Africa, silt/clay ratios in the order of those encountered in the three soil groups indicate a Pleistocene age of soil parent materials (Van Wambeke, 1962, p. 128). Supporting evidence is provided

TABLE 5.--Mean International Silt/Clay Ratios[a] of A and B2 Horizons of Modern Soils in Southern San Carlos

Soil Groups	$\frac{ISiA}{CA}$	$\frac{ISiB2}{CB2}$
Loma Buenos Aires (PP)[b] N = 1	1.27	2.38
Alluvial Plains (ALP)[c] N = 1	0.89	1.08
Alluvial/Laharic Fans (PP) N = 5	1.07	0.45
La Josefina (PP) N = 2[d]	0.74	0.24
Tilted Fault-Block Ridges (PP) N = 17[e]	0.60	0.18
Small Hills of Laharic Origin (ALP) N = 5	0.44	0.10
Cerro Los Chiles (PP) N = 1	0.16	0.04

[a]International silt/clay ratios are used for comparison with work done in the humid tropics by non-U.S. authors.

[b]Piedmont Province.

[c]Atlantic Lowland Province.

[d]For A horizon N = 1.

[e]For A horizon N = 16.

by three radiocarbon dates, obtained on wood samples collected near the base of the backslope of tilted fault-block ridge II (Chapter I, p. 8), which indicate that the tectonic landforms in southern San Carlos are older than 40,000 years.

Of the three soil groups, the soils on alluvial/laharic fans have the highest mean silt/clay ratios in both epipedons and subsoil horizons. The relatively high mean silt/clay ratio for the soil-surface horizon arises because the soils on two of the three fans represented in the sample have comparatively high mean silt/clay ratios in epipedons. They are 1.40 and 1.08 as compared to 0.62 for the third fan. Since subsoil mean silt/clay ratios for the two fans are distinctly lower, 0.53 and 0.49, respectively, the mean silt/clay ratios for soil-surface horizons are interpreted to reflect the addition of more recent, shallow sediments to the surfaces of the two fans. The soils on pyroclastic deposits in the vicinity of La Josefina have lower mean silt/clay ratios in both epipedons and subsoil horizons than the soils on alluvial/laharic fans. Of greatest importance is the distinctly lower mean silt/clay ratio for subsoil horizons in these soils, which clearly indicates that the soils near La Josefina are older than the soils on alluvial/laharic fans. The soils on tilted fault-block ridges have lower mean silt/clay ratios in both epipedons and subsoil horizons than the soils in the vicinity of La Josefina. For this reason, they are considered to be the oldest soils among the three soil groups which are at an intermediate stage of soil development.

The two soil groups which on the basis of mean soil texture are considered to be at an advanced stage of soil development have the lowest mean silt/clay ratios in both epipedons and subsoil horizons of all modern soils in southern San Carlos (Table 5). Differences in mean silt/clay ratios between the two soil groups suggest more strongly than did differences in mean soil texture that the soils on the cinder cone Cerro Los Chiles are older than the soils on small hills of laharic origin in the Atlantic Lowland Province of the study area. Moreover, considering the extremely low mean silt/clay ratios for the subsoil horizons of the two soil groups, both may date from the Tertiary Period. In the Congo Basin of Central Africa, such low silt/clay ratios indicate a pre-Pleistocene age of soil parent materials (Van Wambeke, 1962, p. 128). The parent materials of the two soil groups possibly are Pliocene in age because there was renewed geologic instability at that time which created the Cordillera Central of Costa Rica. The assessed ages for the two soil groups disagree with information provided on a recent geologic map of Costa Rica on which all outcrops in southern San Carlos are assigned a Quaternary age (Ministerio de Industria y Comercio, 1968).

Illuvial-Clay Content and Relative Soil Ages

Illuvial-clay content is a less valuable criterion for establishing relative ages of modern soils in southern San Carlos than the two previously discussed pedogenic properties. This stems in part from the binary nature of the illuvial-clay data, which does not permit age distinctions beyond two general categories of soil development. Argillans are absent from the subsoil horizons of the three soil groups which on the basis of mean soil texture and silt/clay ratios are considered to represent the youngest soils in southern San Carlos. On the other hand, argillans are present in the subsoil horizons of all other soils in the study area (Table 6).

The absence of argillans from the soils on the cinder cone Loma Buenos Aires and from the soils on alluvial plains in the Atlantic Lowland Province of southern San Carlos supports previous evidence on the basis of which these two soil groups are judged to be at an early stage of soil development. In contrast, of the three soil groups which are considered to be at an intermediate stage of soil development only the two older soil groups in the vicinity of La Josefina and on tilted fault-block ridges contain argillans in subsoil horizons. The absence of argillans from the subsoil horizons of the soils on alluvial/laharic fans seems to indicate that the clay in the lower part of soil sola has formed *in situ*. It may also in part have been inherited, since variations in subsoil clay content

TABLE 6.--Presence of Argillans in Subsoil Horizons of Modern Soils in Southern San Carlos

Soil Groups	Number No	Number Yes
Loma Buenos Aires (PP)[a] N = 1	1	0
Alluvial Plains (ALP)[b] N = 1	1	0
Alluvial/Laharic Fans (PP) N = 5	5	0
La Josefina (PP) N = 2	0	2
Tilted Fault-Block Ridges (PP) N = 17	1	16
Small Hills of Laharic Origin (ALP) N = 5	0	5
Cerro Los Chiles (PP) N = 1	0	1

[a]Piedmont Province.

[b]Atlantic Lowland Province

among soils on different fans appear to reflect differences in the clay content of parent materials. Moreover, the cumulative nature of many of the alluvial soils may have contributed to the lack of illuvial clay by denying respective surface soils sufficient time for the initiation of clay transfer. The data suggest that the soils on alluvial/laharic fans probably are not truly at an intermediate stage of soil development despite the relatively high clay content in subsoil horizons. On the other hand, because of a higher total clay content in subsoil horizons these soils must be considered older than the soils on the cinder cone

Loma Buenos Aires and the soils on alluvial plains in the Atlantic Lowland Province of southern San Carlos.

Although soils at an advanced stage of soil development are generally expected to display a lower degree of clay illuviation than soils at an intermediate stage of soil development (Hypothesis 3), well-developed argillans are present in the subsoil horizons of the two soil groups considered to be at an advanced stage of soil development. The presence of argillans may be related to the low shrink-swell potential of the predominant 1:1 layer silicate and hydrous-oxide clays and the exceptional structural stability exhibited by these soils (Appendix III; Harris, 1971, p. 161; Harris et al., 1971, p. 442-443). As clay content increased, argillans, rather than being destroyed and incorporated into the subsoil matrix, may have been retained, even as soil texture was becoming exceedingly fine.

Soil Color and Relative Soil Ages

Soil color, as illuvial-clay content, is also a less valuable criterion for establishing relative ages of modern soils in southern San Carlos than mean soil texture and silt/clay ratios. Although soils tend to become redder with increasing degree of soil development, as indicated by a gradual progression from 10YR to 2.5YR color hues and a quantitative increase in soils with redder color hues within individual soil groups, only two categories of soil development can be established on the basis of differences in soil color.

In general, less-developed or younger soils in southern San Carlos are characterized by 10YR and 7.5YR color hues, identical color hues in epipedons and subsoil horizons, and chromas of 4 in subsoil horizons. The soils on the cinder cone Loma Buenos Aires, on alluvial plains in the Atlantic Lowland Province, on pyroclastic deposits in the vicinity of La Josefina, and on alluvial/laharic fans are included in this category (Table 7). More highly developed or older soils in the study area generally have 5YR and 2.5YR color hues, redder color hues in subsoil than in soil-surface horizons, and chromas stronger than 4 in subsoil horizons. This category includes the soils on tilted fault-block ridges, on small hills of laharic origin in the Atlantic Lowland Province, and on the cinder cone Cerro Los Chiles (Table 7).

Relative ages of individual soil groups among the younger soils in the study area are extremely difficult to determine because of similarity or overlap in soil colors. Although it appears that the soils on Loma Buenos Aires are the youngest soils in this category, one of the soils on the alluvial/laharic fans has identical 10YR color hues in both soil-surface and subsoil horizons. Moreover, although the soils on the alluvial plains in the Atlantic Lowland Province and the soils near La Josefina are thought to be older than the soils on Loma Buenos Aires because of redder color hues throughout soil sola, age distinctions between

TABLE 7.--Color Hues of A Horizons and Reddest Color Hues and Strongest Chromas of B2 Horizons of Modern Soils in Southern San Carlos

Soil Groups	A			B2					
	Hue	N	%	Hue	N	%	Chroma	N	%
Loma Buenos Aires (PP)[a] N = 1	10YR	1	100	10YR	1	100	4	1	100
Alluvial Plains (ALP)[b] N = 1	7.5YR	1	100	7.5YR	1	100	4	1	100
Alluvial/Laharic Fans (PP) N = 5	10YR 7.5YR	2 3	40 60	10YR 7.5YR 5YR	3 1 1	60 20 20	4	5	100
La Josefina (PP) N = 2	7.5YR	2	100	7.5YR	2	100	4	2	100
Tilted Fault-Block Ridges (PP) N = 17[c]	10YR 7.5YR 5YR 2.5YR	4 5 6 1	25 31 38 6	7.5YR 5YR 2.5YR	4 7 6	24 41 35	4 5 6 7	7 1 7 2	41 6 41 12
Small Hills of Laharic Origin (ALP) N = 5	5YR	5	100	2.5YR	5	100	6	5	100
Cerro Los Chiles (PP) N = 1	2.5YR	1	100	2.5YR	1	100	7	1	100

[a]Piedmont Province. [b]Atlantic Lowland Province. [c]For A horizon N = 16.

these two soil groups cannot be made because of same soil colors. Lastly, the apparent variability in soil colors among the soils on alluvial/laharic fans, previously judged to be intermediate in age between the latter two soil groups, further complicates the issue. For these reasons, it is felt that clear age distinctions between individual soil groups among the younger soils in southern San Carlos cannot be made on the basis of differences in soil color.

Relative ages of individual soil groups are more easily determined among the older than among the younger soils in the study area. Although some soils on the tilted fault-block ridges have colors similar to the soils on the small hills of laharic origin (N = 5) and to the soils on Cerro Los Chiles (N = 1), two-thirds of the soils on the tilted fault-block ridges have yellower colors than the soils on the other two landforms. Moreover, the soils on the small hills of laharic origin have yellower color hues in epipedons and weaker chromas in subsoil horizons than the soils on Cerro Los Chiles. These color differences suggest that the soils on tilted fault-block ridges are the youngest and those on the cinder cone Cerro Los Chiles are the oldest among the three soil groups.

Free Iron-Oxide Content and Relative Soil Ages

The free iron-oxide data support soil-textural evidence on the basis of which two groups of modern soils in southern San Carlos are considered to be at an early stage, three at an intermediate stage, and two at an advanced stage of soil development. In general, free iron-oxide content of soils increases with increasing degree of soil development. Although this trend can be observed in both epipedons and subsoil horizons, percentages of free iron oxides are normally lower in soil-surface than in subsoil horizons (Table 8).

The soils on the cinder cone Loma Buenos Aires and the soils on the alluvial plains in the Atlantic Lowland Province of southern San Carlos, which are considered to be at an early stage of soil development, have the lowest percentages of free iron oxides throughout soil sola among the modern soils in the study area. Percentages of free iron oxides in epipedons are almost identical for the two soil groups. On the other hand, subsoil content of free iron oxides is substantially higher in the soils on the cinder cone than in the soils on the Atlantic Lowland alluvial plains (Table 8). These data on free iron oxides are contrary to other evidence on the basis of which the soils on Loma Buenos Aires are considered to be the younger of the two soil groups. Considering that both soil groups developed on parent materials with identical textures, the differences in subsoil content of free iron oxides between the two soil groups may reflect differences in the iron content of respective parent materials and/or differences in topographic position.

The soils on alluvial/laharic fans, the soils in the vicinity of La Josefina, and the soils on tilted fault-block

TABLE 8.--Free Iron-Oxide Contents of A and B2 Horizons of Modern Soils in Southern San Carlos

Soil Groups	Mean % of Fe_2O_3 in A Horizon	Mean % of Fe_2O_3 in B2 Horizon	Mean Highest % of Fe_2O_3 in B2 Horizon
Loma Buenos Aires (PP)[a] N = 1	6.0	7.3	7.3
Alluvial Plains (ALP)[b] N = 1	5.9	5.8	5.9
Alluvial/Laharic Fans (PP) N = 5	7.0	8.1	8.5
La Josefina (PP) N = 1[c]	6.8	8.2	8.7
Tilted Fault-Block Ridges (PP) N = 17[d]	7.3	8.0	8.6
Small Hills of Laharic Origin (ALP) N = 5	7.8	8.7	9.4
Cerro Los Chiles (PP) N = 1	9.1	9.0	9.7

[a]Piedmont Province.

[b]Atlantic Lowland Province.

[c]The soil at site 6 was excluded because there is evidence that the relatively high free iron-oxide content of this soil did not result solely from pedogenic weathering but was in part derived from laterally moving ground water.

[d]For A horizon N = 16.

ridges, which are considered to be at an intermediate stage of soil development, exhibit distinctly higher percentages of free iron oxides throughout soil sola than the two soil groups at an early stage of soil development. However, differences in the free iron-oxide contents between the three soil groups are so small in both epipedons and subsoil horizons that age distinctions between them cannot be made (Table 8).

The soils on small hills of laharic origin in the Atlantic Lowland Province of southern San Carlos and the soils on the cinder cone Cerro Los Chiles, which are considered to be at an advanced stage of soil development, show the highest percentages of free iron oxides throughout soil sola among the modern soils in the study area. Although differences in the free iron-oxide contents between the subsoil horizons of the two soil groups are small, the soils on the cinder cone contain a substantially higher amount of free iron oxides in the surface horizon than the soils on laharic parent materials (Table 8). Topographic positions of soils in the two soil groups are similar. Provided that there exist no large differences in the iron content of respective parent materials, the free iron-oxide data may indicate a slightly greater age for the soils on Cerro Los chiles than for the soils on small hills of laharic origin.

Summary

The preceding discussion demonstrated that differences in degree of soil development between modern soils in southern San Carlos can be determined on the basis of differences in pedogenic properties. Of the five pedogenic properties investigated in this study, silt/clay ratios and soil texture are the most sensitive indicators of relative soil ages. Free iron-oxide content, soil color, and illuvial-clay content are less discriminatory but in general support the findings obtained from the other two pedogenic properties (Table 9).

On the basis of differences in overall soil characteristics, seven modern soil groups of different ages can be distinguished in southern San Carlos. Listed in order of increasing soil age, these are: (1) soils on the cinder cone Loma Buenos Aires, extending eastward to the village of Venecia, in the southeastern part of the Piedmont Province; (2) soils on alluvial plains in the Atlantic Lowland Province; (3) soils on alluvial/laharic fans in the south-central part of the Piedmont Province; (4) soils on pyroclastic deposits in the vicinity of La Josefina in the northeastern part of the Piedmont Province; (5) soils on tilted fault-block ridges in the northwestern, northcentral, and central parts of the Piedmont Province; (6) soils on small hills of laharic origin in the Atlantic Lowland Province; and (7) soils on the cinder cone Cerro Los Chiles in the eastcentral part of the Piedmont Province (Table 9).

TABLE 9.--Modern Soils in Southern San Carlos Ranked According to Differences in Degree of Soil Development Established on the Basis of Differences in Pedogenic Properties[a]

Soil Groups	Mean Soil Texture	Mean Silt/Clay Ratios	Mean Free Iron-Oxide Content	Soil Color	Argillans in Subsoil Horizons	All Pedogenic Properties	Stage of Soil Development
Loma Buenos Aires (PP)[b] N = 1	1	1	1	1	1	5	E[c]
Alluvial Plains (ALP)[d] N = 1	2	2	1	1	1	7	E
Alluvial/Laharic Fans (PP) N = 5	3	3	2	1	1	10	I[e]
La Josefina (PP) N = 2	4	4	2	1	2	13	I
Tilted Fault-Block Ridges (PP) N = 17	5	5	2	2	2	16	I
Small Hills of Laharic Origin (ALP) N = 1	6	6	3	3	2	20	A[f]
Cerro Los Chiles (PP) N = 1	7	7	4	4	2	24	A

[a]Numbers become higher with increasing degree of soil development.

[b]Piedmont Province. [c]Early.

[d]Atlantic Lowland Province. [e]Intermediate.

[f]Advanced.

The first two of these soils groups are considered to be at an early stage, the next three at an intermediate stage, and the last two at an advanced stage of soil development. Absolute ages of the differing soil groups can be inferred from silt/clay ratios in subsoil horizons (Van Wambeke, 1962, p. 128). The parent materials of the first two soil groups are Recent, those of the next three soil groups Pleistocene, and those of the last two soil groups pre-Pleistocene, most likely Pliocene, in age.

Paleosols

The number of paleosols for which detailed soil data are available is relatively small because paleosols are present at only 11 of the 34 major soil sampling sites. Two paleosols occur in the Atlantic Lowland Province of southern San Carlos, including one on alluvium in the eastern part and one on a small hill of laharic origin in the western part of this area. The remaining nine paleosols are found in the Piedmont Province of the study area. One paleosol each is present on the cinder cone, Loma Buenos Aires, in the southeastern part and on pyroclastic deposits in the vicinity of the village of La Josefina in the northeastern part of this area. Seven paleosols, three of which occur at one sampling site (31), are located on tilted fault-block ridges in the northwestern, northcentral, and central parts of the area (Fig. 39).

All paleosols are buried soils in which A horizons are missing or are preserved to varying degrees. For this reason, differences in subsoil characteristics are considered to be more highly indicative of relative ages of paleosols than differences in A-horizon characteristics. Differences in degree of soil development of paleosols are established on the basis of differences in the same diagnostic pedogenic properties as for modern soils.

Soil Texture and Relative Soil Ages

On the basis of differences in mean soil texture, five groups of paleosols can be distinguished in southern San Carlos. Textural characteristics imply that one is at an early stage, three are at an intermediate stage, and one is at an advanced stage of soil development (Hypothesis 1). Additional age distinctions can be made between the paleosols which are considered to be at an intermediate stage of soil development.

The paleosol which is considered to be at an early stage of soil development occurs on an alluvial plain in the eastern part of the Atlantic Lowland Province of southern San Carlos. Compared to the paleosols which are considered to be at an intermediate stage of soil development, this paleosol has a notably coarser texture in both A and B2 horizons (Table 10). Although differences in soil textures may in part stem from differences in the texture of respective parent materials, certain textural characteristics indicate that the buried soil on the alluvial plain has experienced a relatively low degree of soil development. The parent material of this paleosol is a sandy loam

TABLE 10.--Mean Texture of A and B2 Horizons of Paleosols in Southern San Carlos

Soil Groups	Sand A	Silt A	Clay A	Textural Classes		Sand B2	Silt B2	Clay B2	Textural Classes	
				Basic[a]	General[b]				Basic	General
Alluvial Plains (ALP)[c] N = 1	48	32	20	Loam	m[d], fl[e]	25	53	22	Silt Loam	m, fl
La Josefina (PP)[f] N = 1	26	39	35	Clay Loam	mf[g], fl/fc[h]	30	22	49	Clay	f[i], fc
Loma Buenos Aires (PP) N = 1[j]	--	--	--	--	--	29	20	52	Clay	f, fc
Tilted Fault-Block Ridges (PP) N = 7[k]	28	28	45	Clay	f, fc	21	19	62	Clay	f, vfc[l]
Small Hills of Laharic Origin (ALP) N = 1	23	12	65	Clay	f, vfc	18	11	71	Clay	f, vfc

[a]Soil Survey Staff, 1951, p. 207-211.

[b]Soil Survey Staff, 1951, p. 213; Buol, Hole, and McCracken, 1973, p. 27.

[c]Atlantic Lowland Province.

[d]Medium-textured soils.

[e]Fine loamy soils.

[f]Piedmont Province.

[g]Moderately fine-textured soils.

[h]Fine clayey soils.

[i]Fine-textured soils.

[j]For A horizon N = 0.

[k]For A horizon N = 3.

[l]Very fine clayey soils.

or is moderately coarse or coarse loamy in texture. The buried soil has a medium or fine loamy texture in both A and B2 horizons (Table 10). Although silt content is greater in the subsoil than in the A horizon, clay content is relatively low and very similar in both soil horizons. Both the low clay content and the lack of a pronounced horizon differentiation with regard to clay content indicate that the buried soil on the alluvial plain in the eastern part of the Atlantic Lowland Province of the study area is at an early stage of soil development (Hypothesis 1).

Paleosols which are considered to be at an intermediate stage of soil development are present on pyroclastic deposits in the vicinity of La Josefina, on the cinder cone Loma Buenos Aires, and on tilted fault-block ridges in the Piedmont Province of southern San Carlos. Compared to the previously discussed paleosol, they possess distinctly finer mean textures throughout soil sola (Table 10). They also show a pronounced horizon differentiation with regard to clay content, a trait characteristic of soils at an intermediate stage of soil development (Hypothesis 1).

The know parent-material textures of four of the paleosols are similar. The parent material of the buried soil near La Josefina and of one buried soil on tilted fault-block ridges is a clay loam or is moderately fine or fine clayey in texture. The parent material of two buried soils on tilted fault-block ridges is a clay or is fine or fine clayey in texture. Therefore, differences in soil texture among the paleosols at an intermediate stage of soil development can be attributed to differences in duration of soil formation rather than to differences in the texture of parent materials.

The subsoil horizons of the buried soil near La Josefina and of the buried soil on Loma Buenos Aires are both fine or fine clayey in texture. This indicates that the two paleosols have experienced a similar degree of soil development. The buried soils on tilted fault-block ridges have a substantially finer mean epipedon texture than the buried soil near La Josefina and a distinctly finer mean subsoil texture than both the buried soil near La Josefina and the buried soil on Loma Buenos Aires (Table 10). Therefore, the buried soils on tilted fault-block ridges have experienced the greatest degree of soil development among the paleosols which are considered to be at an intermediate stage of soil development.

The buried soil which is considered to be at an advanced stage of soil development occurs on a small hill of laharic origin in the western part of the Atlantic Lowland Province of southern San Carlos. Although this paleosol has the same mean texture designation in the subsoil horizon as the buried soils on tilted fault-block ridges, it contains a greater amount of subsoil clay than the latter soils (Table 10). Most importantly, the buried soil on the small hill of laharic origin shows a substantially smaller degree of horizon differentiation with regard to clay content than the paleosols which are considered to be at an intermediate stage of soil development, a trait characteristic of soils at an advanced stage of soil development (Hypothesis 1).

<u>Silt/Clay Ratios and Relative Soil Ages</u>

On the basis of differences in mean silt/clay ratios of subsoil horizons, four groups of paleosols can be distinguished in southern San Carlos. The data show more clearly than did differences in mean soil texture that two paleosols in the eastern part of the Piedmont Province of the study area have experienced a similar degree of soil development.

The buried soil on the Atlantic Lowland alluvial plain has a substantially higher mean silt/clay ratio in the subsoil horizon than the other paleosols in southern San Carlos (Table 11). This supports previous evidence on the basis of which this paleosol is considered to be at an early stage of soil development. Moreover, the relatively high mean silt/clay ratio in the subsoil horizon of the buried soil indicates that the alluvial parent material is Recent in age (Van Wambeke, 1962, p. 128).

The paleosols which on the basis of mean soil texture are considered to be at an intermediate stage of soil development have distinctly lower mean silt/clay ratios in the subsoil horizon than the paleosol which is considered to be at an early stage of soil development (Table 11).

TABLE 11.--Mean International Silt/Clay Ratios[a] of B2 Horizons of Paleosols in Southern San Carlos

Soil Groups	$\frac{ISiB2}{CB2}$
Alluvial Plains (ALP)[b] N = 1	0.82
La Josefina (PP)[c] N = 1	0.33
Loma Buenos Aires (PP) N = 1	0.33
Tilted Fault-Block Ridges (PP) N = 7	0.26
Small Hills of Laharic Origin (ALP) N = 1	0.13

[a]International silt/clay ratios are used for comparison with work done in the humid tropics by non-U.S. authers.

[b]Atlantic Lowland Province.

[c]Piedmont Province.

Moreover, mean silt/clay ratios in the subsoil horizons of these paleosols indicate that soil parent materials are Pleistocene in age (Van Wambeke, 1962, p. 128). The buried soils in the vicinity of La Josefina and on Loma Buenos Aires have identical mean silt/clay ratios in subsoil horizons. These data substantiate previous evidence on the basis of which these two paleosols are considered to have experienced a similar degree of soil development. Both paleosols also have higher mean silt/clay ratios in subsoil horizons than the buried soils on tilted fault-block ridges. This indicates that they have experienced a lesser degree of soil development than the paleosols on the tectonic landforms.

The buried soil on the small hill of laharic origin in the Atlantic Lowland Province of the study area has the lowest mean silt/clay ratio in the subsoil horizon among the paleosols in southern San Carlos (Table 11). This supports previous evidence on the basis of which this paleosol is considered to be at an advanced stage of soil development. Moreover, the low mean silt/clay ratio in the subsoil horizon of the buried soil indicates that the laharic parent material is pre-Pleistocene, most likely Pliocene, in age (Van Wambeke, 1962, p. 128).

Illuvial-Clay Content and Relative Soil Ages

Illuvial-clay content is a less valuable criterion for establishing relative ages of paleosols in southern San Carlos than mean silt/clay ratios and mean soil texture because argillans are present in the subsoil horizons of all but two of the paleosols. As in modern soils, illuvial-clay content does not permit separation of soils at an intermediate stage of soil development from soils at an advanced stage of soil development.

The absence of argillans from the subsoil horizon of the buried soil on the alluvial plain in the Atlantic Lowland Province of southern San Carlos supports previous evidence on the basis of which this paleosol is considered to be at an early stage of soil development (Table 12).

Of the paleosols which are considered to be at an intermediate stage of soil development, only the buried

TABLE 12.--Presence of Argillans in Subsoil Horizons of Paleosols in Southern San Carlos

Soil Groups	Number No	Number Yes
Alluvial Plains (ALP)[a] N = 1	1	0
La Josefina (PP)[b] N = 1	1	0
Loma Buenos Aires (PP) N = 1	0	1
Tilted Fault-Block Ridges (PP) N = 7	0	7
Small Hills of Laharic Origin (ALP) N = 1	0	1

[a]Atlantic Lowland Province.

[b]Piedmont Province.

soil on Loma Buenos Aires and the buried soils on tilted fault-block ridges contain argillans in subsoil horizons (Table 12). The absence of argillans from the subsoil horizon of the buried soil in the vicinity of La Josefina indicates that the clay in the lower part of the solum of this paleosol has formed _in situ_ and/or has been inherited from the parent material. However, the absence of argillans from the subsoil horizon of the buried soil near La Josefina does not necessarily contradict previous evidence on the basis of which a similar degree of soil development is inferred for this paleosol and the buried soil on Loma Buenos Aires, since the argillans in the subsoil horizon of the latter paleosol are few and weakly developed. On the other hand, the lack and minor presence of illuvial clay in the subsoil horizons of the two paleosols questions their assessed stage of soil development. Apparently, both paleosols inherited some clay from their respective parent materials and are less highly developed than is indicated by their subsoil textures and silt/clay ratios. In contrast, in the subsoil horizons of the buried soils on tilted fault-block ridges argillans are mostly well developed and common. This supports previous evidence on the basis of which these paleosols are considered to have experienced a greater degree of soil development than the paleosols on pyroclastic parent materials in the eastern part of the Piedmont Province of the study area.

The buried soil on the small hill of laharic origin in the Atlantic Lowland Province of southern San Carlos, which on the basis of previous evidence is considered to be at an advanced stage of soil development, contains numerous, well-developed argillans in the subsoil horizon (Table 12). As clay content increased, argillans apparently were retained for the same reasons as in modern soils at an advanced stage of soil development (p. 125).

Soil Color and Relative Soil Ages

Of the three color criteria used to establish two broad age categories of soil development in modern soils, only one shows a similar trend in paleosols as in modern soils. Whereas color hues generally become redder with increasing degree of soil development in both modern and buried soils, differences in color hues between A and B2 horizons and subsoil chromas stronger than 4 are evident at yellower color hues in paleosols than they are in modern soils. For this reason, differences in degree of soil development are even more difficult to assess on the basis of differences in soil color than in modern soils.

Although identical color hues in both A and B2 horizons indicate a relatively low degree of soil development for the buried soil on the alluvial plain in the Atlantic Lowland Province of southern San Carlos (Hypothesis 4), differences in color hues do not permit to separate this paleosol from all other paleosols in the study area (Table 13). Moreover, because of a stronger subsoil chroma the buried soil on the Atlantic Lowland alluvial plain may have experienced a slightly higher degree of soil development than the buried soil on Loma Buenos Aires, previously believed to be more highly developed than the former paleosol. On the other hand, because of yellower color hues in subsoil horizons both paleosols appear to have experienced a lesser degree of soil development than the buried soil in the vicinity of La Josefina (Table 13).

In general, the buried soils on tilted fault-block ridges have experienced a greater degree of soil development than the previously mentioned paleosols because the majority of A horizons and 43 percent of subsoil horizons in the paleosols on the tectonic landforms have redder color hues than respective soil horizons in the other paleosols (Table 13). On the other hand, differences in

TABLE 13.--Color Hues of A Horizons and Reddest Color Hues and Strongest Chromas of B2 Horizons of Paleosols in Southern San Carlos

Soil Groups	A			B2					
	Hue	N	%	Hue	N	%	Chroma	N	%
Alluvial Plains (ALP)[a] N = 1	7.5YR	1	100	7.5YR	1	100	6	1	100
La Josefina (PP)[b] N = 1	7.5YR	1	100	5YR	1	100	6	1	100
Loma Buenos Aires (PP) N = 1[c]	--	--	--	7.5YR	1	100	4	1	100
Tilted Fault-Block Ridges (PP) N = 7[d]	7.5YR 2.5YR	1 2	33 67	7.5YR 5YR 2.5YR	1 3 3	14 43 43	4 5 6	2 1 4	29 14 57
Small Hills of Laharic Origin (ALP) N = 1	5YR	1	100	2.5YR	1	100	6	1	100

[a]Atlantic Lowland Province.

[b]Piedmont Province.

[c]For A horizon N = 0.

[d]For A horizon N = 3.

soil color do not permit to distinguish the buried soil on the small hill of laharic origin in the Atlantic Lowland Province, previously believed to have experienced the highest degree of soil development among the paleosols in southern San Carlos, from the reddest paleosols on tilted fault-block ridges because of identical color hues and chromas in subsoil horizons (Table 13).

Free Iron-Oxide Content and Relative Soil Ages

In paleosols, as in modern soils, variations in the free iron-oxide content of subsoil horizons support soil-textural evidence on the basis of which one paleosol is considered to be at an early stage, one at an advanced stage, and three groups of paleosols are considered to be at an intermediate stage of soil development. In general, the free iron-xode content in the subsoil horizons of paleosols increases with increasing degree of soil development. However, one paleosol at an intermediate stage of soil development shows an anomalously high amount of free iron oxides in the subsoil horizon, the origin of which is not entirely clear.

The buried soil on the alluvial plain in the Atlantic Lowland Province of the study area has the lowest percentages of free iron oxides in the subsoil horizon among the paleosols in southern San Carlos (Table 14). The data support previous evidence on the basis of which this paleosol is considered to be at an early stage of soil development.

TABLE 14.--Free Iron-Oxide Content of B2 Horizons of Paleosols in Southern San Carlos

Soil Groups	Mean % of Fe_2O_3 in B2 Horizon	Mean Highest % of Fe_2O_3 in B2 Horizons
Alluvial Plains (ALP)[a] N = 1	6.6	6.6
La Josefina (PP)[b] N = 1	8.0	8.3
Loma Buenos Aires (PP) N = 1	9.0	9.4
Tilted Fault-Block Ridges (PP) N = 7	7.8	8.1
Small Hills of Laharic Origin (ALP) N = 1	8.8	9.7

[a]Atlantic Lowland Province.

[b]Piedmont Province.

The paleosols which are considered to be at an intermediate stage of soil development have distinctly higher percentages of free iron oxides in the subsoil horizon than the buried soil on the alluvial plain in the Atlantic Lowland Province (Table 14). However, differences in the percentages of free iron oxides between the buried soil in the vicinity of La Josefina and the buried soils on tilted fault-block ridges are so small that these paleosols cannot be distinguished on the basis of differences in free iron-oxide content of subsoil horizons. On the other hand, the buried soil on Loma Buenos Aires contains an unexpectedly high amount of free iron oxides in the subsoil horizon, especially considering other properties of this paleosol, which are similar to those in the buried soil near La Josefina. The differences in the subsoil content of free iron oxides between the two paleosols may reflect differences in the iron content of respective parent materials. Alternatively, the higher free iron-oxide content in the subsoil horizon of the buried soil on Loma Buenos Aires, located on a steeper slope than the buried soil near La Josefina, may in part be due to precipitation of iron from laterally moving soil water. Unfortunately, firm evidence for either mode of origin is not available.

The buried soil on the small hill of laharic origin in the Atlantic Lowland Province contains the highest percentage of free iron oxides in the subsoil horizon among the paleosols in southern San Carlos (Table 14). Although mean subsoil content of free iron oxides in this paleosol is slightly lower than that in the buried soil on Loma Buenos Aires, the buried soil on the laharic parent material can still be considered the most highly developed paleosol in the study area. The free iron-oxide data are in support of previous evidence in view of the fact that reasons for the relatively high subsoil content of free iron oxides in the buried soil on Loma Buenos Aires are unclear and that the subsoil content of free iron oxides is notably lower in the buried soils near La Josefina and on tilted fault-block ridges than in the buried soil on the small hill of laharic origin.

Summary

Although soil data for the A horizons of almost half of the paleosols are unavailable because of poor preservation of the upper part of soil sola, differences in degree of soil development between paleosols in southern San Carlos can be determined on the basis of differences in pedogenic properties. As in modern soils, silt/clay ratios and soil texture are the most sensitive indicators of relative soil ages. On the other hand, free iron-oxide content, soil color, and illuvial-clay content not only are less discriminatory than the other two pedogenic properties, as in modern soils, but they also are somewhat less indicative of relative degree of soil development than they are in modern soils (Table 15).

On the basis of differences in overall soil characteristics, the paleosols in southern San Carlos can be divided into four different age groups. Listed in order of increasing soil age, these include: (1) the buried soil on the alluvial plain in the eastern part of the Atlantic Lowland Province; (2) the buried soils on pyroclastic parent materials in the vicinity of La Josefina and on Loma Buenos

TABLE 15.--Paleosols in Southern San Carlos Ranked According to Differences in Degree of Soil Development Established on the Basis of Differences in Pedogenic Properties[a]

Soil Groups	Mean Soil Texture	Mean Silt/Clay Ratios	Mean Free Iron-Oxide Content	Soil Color	Argillans in Subsoil Horizons	All Pedogenic Properties	Stage of Development
Alluvial Plains (ALP)[b] N = 1	1	1	1	2	1	6	E[c]
La Josefina (PP)[d] N = 1	2	2	2	3	1	10	I[e]
Loma Buenos Aires (PP) N = 1	2	2	3	1	2	10	I
Tilted Fault-Block Ridges (PP) N = 7	3	3	2	4	2	14	I
Small Hills of Laharic Origin (ALP) N = 1	4	4	4	4	2	18	A[f]

[a]Numbers become higher with increasing degree of soil development.

[b]Atlantic Lowland Province.

[c]Early.

[d]Piedmont Province.

[e]Intermediate.

[f]Advanced.

Aires in the eastern part of the Piedmont Province; (3) the buried soils on tilted fault-block ridges in the northwestern, northcentral, and central parts of the Piedmont Province; and (4) the buried soil on the small hill of laharic origin in the western part of the Atlantic Lowland Province (Table 15).

Despite apparent differences in three of the five pedogenic properties investigated in this study, the two buried soils near La Josefina and on Loma Buenos Aires appear to have experienced a similar degree of soil development. Both paleosols are considered to be at an intermediate stage of soil development, as are the buried soils on tilted fault-block ridges. Moreover, on the basis of silt/clay ratios in subsoil horizons the parent materials of these paleosols are believed to date from the Pleistocene Epoch. The buried soil on the alluvial plain and the buried soil on the small hill of laharic origin in the Atlantic Lowland Province are considered to be at an early and at an advanced stage of soil development, respectively. The nature of silt/clay ratios in the subsoil horizons of the two paleosols implies that the alluvial parent material is Recent and the laharic parent material is pre-Pleistocene, probably Pliocene, in age.

Temporal Distribution of Modern and Buried Soils in Southern San Carlos

Both the modern and the buried soils in southern San Carlos show a distinct regional distribution pattern with regard to the two physiographic provinces of the study area. In the Atlantic Lowland Province of southern San Carlos, modern as well as buried soils are either at an early or at an advanced stage of soil development, with the exception of one modern soil, which is at an intermediate stage of soil development. Both the modern and the buried soil on the alluvial plain in the eastern part of the Atlantic Lowland Province are at an early stage of soil development. However, the buried soil shows a slightly higher degree of soil development than the overlying modern soil. Soils at an advanced stage of soil development include four modern soils and one buried soil on small hills of laharic origin. A fifth modern soil, located on a small hill of laharic origin in the western part of the Atlantic Lowland Province, is at an intermediate stage of soil development. The buried soil is present at this locality and at a more advanced stage of soil development than the overlying modern soil. On the other hand, the degree of soil development exhibited by the buried soil is somewhat less than that of modern soils on laharic parent materials which are at an advanced stage of soil development.

In the Piedmont Province of southern San Carlos, all but two modern soils and all buried soils are at an intermediate stage of soil development. One modern soil, located on the cinder cone Loma Buenos Aires in the southeastern part of the Piedmont Province, is at an early stage of soil development. This soil exhibits a somewhat lower degree of soil development than the modern soil on the alluvial plain in the eastern part of the Atlantic Lowland Province, the only other modern soil in the study area which is at an early stage of soil development. Another modern soil on pyroclastic parent materials, located on Cerro Los Chiles in the eastcentral part of the Piedmont Province, is at an advanced stage of soil development. This soil shows a slightly higher degree of soil development than the modern soils on small hills of laharic origin in the Atlantic Lowland Province, the only other modern soils in the study area which are at an advanced stage of soil development.

Soils at an intermediate stage of soil development include the modern soils on alluvial/laharic fans in the southcentral part, the modern soils and one buried soil on pyroclastic parent materials near La Josefina in the northeastern part, the modern and the buried soils on tilted fault-block ridges in the northwestern, northcentral, and central parts, and the buried soil on Loma Buenos Aires in the southeastern part of the Piedmont Province (Fig. 39). Of the modern soils at an intermediate stage of soil development, those on alluvial/laharic fans show the lowest and those on tilted fault-block ridges the highest degree of soil development. The degree of soil development of the modern soils in the vicinity of La Josefina is intermediate between that of the other two soil groups. Of the buried soils at an intermediate stage of soil development, the buried soil near La Josefina and the buried soil on Loma Buenos Aires exhibit a similar and lower degree of soil development than the buried soils on tilted fault-block ridges. With the exception of the buried soil on Loma Buenos Aires, which is at a more advanced stage of soil development than the overlying modern soil, the buried soils in the Piedmont Province of southern San Carlos are at the same stage of soil development as overlying modern soils. However, both the buried soil near La Josefina and the buried soils on tilted fault-block ridges exhibit a slightly lower degree of soil development than overlying modern soils.

The temporal distribution of modern and buried soils in southern San Carlos indicates that episodes of landscape instability have varied in number and have occurred at different times in different parts of the study area. In the Atlantic Lowland Province of southern San Carlos, four episodes of landscape instability are recognizable on the basis of the available soil data. Two early episodes of landscape instability, believed to have occurred during the Pliocene Epoch, led to the formation of small hills of laharic origin. Two very much later, Recent episodes of landscape instability contributed to the buildup of alluvial plains.

In the western and central parts of the Piedmont Province of southern San Carlos, three episodes of landscape instability are documented by the available soil data. All three took place subsequent to the formation of small hills of laharic origin and prior to the latest episode of alluvial deposition in the Atlantic Lowland Province and are believed to date from the Pleistocene Epoch. However, the latest of the three unstable periods, which led to the formation of upper surfaces on alluvial/laharic fans in the southcentral part of the Piedmont Province, occurred at a much later time than the two earlier ones, which were associated with the creation of tilted fault-block ridges in the northwestern, northcentral, and central parts of this area.

In the eastern and eastcentral parts of the Piedmont Province of southern San Carlos, four, possibly five, episodes of landscape instability are distinguishable on the basis of the available soil data. The earliest episode of landscape instability, which led to the buildup of the cinder cone Cerro Los Chiles in the eastcentral part of the Piedmont Province, is believed to have occurred during the Pliocene Epoch immediately prior to or possibly at the same time as the earlier episode of laharic deposition in the Atlantic Lowland Province. The next episode(s) of landscape instability, which caused widespread pyroclastic deposition in the eastern part of the Piedmont Province, are believed to have taken place during the Pleistocene Epoch after tectonic movements initiated the formation of tilted fault-block ridges in the northwestern, northcentral, and central parts of the Piedmont Province. The third or fourth episode of landscape instability, which is responsible for the deposition of pyroclastic surface materials in the northeastern part of the Piedmont Province, also occurred during the Pleistocene Epoch prior to the latest addition of sediments to the surfaces of alluvial/laharic fans in the southcentral part of the Piedmont Province. The latest episode of landscape instability, which caused the deposition of pyroclastic surface materials on Loma Buenos Aires and in the area east of the cinder cone in the southeastern part of the Piedmont Province, is Recent in age and postdates the latest episode of alluvial deposition in the Atlantic Lowland Province.

In summary, information which can be obtained from the temporal distribution of modern and buried soils in southern San Carlos greatly enhances previous knowledge, gained from geomorphic evidence, about relative ages of landforms in the study area. As is evident from the preceding discussion, the soil data permit an assessment of age relationships between spatially disjunct landforms. Moreover, pedogenic evidence provides a better understanding of the magnitude of age differences between landforms. As a result, relative ages of most landforms in southern San Carlos can be determined and major episodes of landscape evolution in the region can be established. Both topics are treated in the following chapter of the dissertation.

CHAPTER IV

CONCLUSIONS

Introduction

In this chapter, the most important results from landform and soil studies are stated, inferences from soil studies about the temporal distribution of landforms are discussed, and major episodes of landscape evolution in southern San Carlos are outlined.

Results from Landform Studies

The methods employed in the study of landforms, including various field observations and the use of vertical and oblique aerial photographs and topographic maps, were adequate to determine the origin and spatial distribution of major landform types in southern San Carlos. The study could have been enhanced by (1) systematic topographic surveying of low-relief features, such as small hills of laharic origin and stream terraces; (2) successful use of coring equipment as an aid in the more precise delineation of landform boundaries; (3) a larger number of detailed stratigraphic and boulder-orientation studies; and (4) more success in the search for materials suitable for radiocarbon dating.

In the Atlantic Lowland Province of southern San Carlos, three major landform types are recognizable: small hills of laharic origin; alluvial plains; and stream terraces.

(1) According to available field evidence and the interpretation of topographic maps and aerial photographs, rapid mass flowages in the form of lahars are responsible for the formation of small hills which are present throughout the Atlantic Lowland Province, especially since other modes of origin, including dissected alluvial plains, isolated cinder cones, and lava flows, can be ruled out.

(2) Fluvial aggradation has been more widespread in the Atlantic Lowland Province than previously recognized, as evidenced by the prevalence of alluvial plains in areas currently not traversed by streams. The composition and sequence of alluvial deposits suggest importation of sediments from relatively unweathered, extralocal source areas, located in the Mountainous and Piedmont Provinces of southern San Carlos, during successive episodes of increased fluvial aggradation of varying durations.

(3) The presence of low-level paired terraces, which occur at and below the level of alluvial plains adjacent to present-day stream channels, indicates that episodes of increased fluvial aggradation were followed by brief, successive episodes of increased fluvial degradation. Available field evidence is inconclusive as to the exact origin of these terraces. Two paired terraces which are present

along the lowland reach of the Río Kopper may have resulted from successive channel adjustments of the Río Aguas Zarcas. Alternatively, the formation of these terraces may have occurred in response to episodic lowering of the local base level, caused by successive downcutting of the Río San Carlos.

In the Piedmont Province of southern San Carlos, the four major landform types are: tilted fault-block ridges; alluvial/laharic fans; alluvial plains; and cinder cones and associated pyroclastic deposits.

(1) Evidence for a tectonic origin of three ridges, which ascend in steplike fashion in the northwestern, northcentral, and central parts of the Piedmont Province, is provided by: (a) abruptly rising, steep front scarps; (b) the widespread occurrence of landslides of varying sizes along scarps; (c) triangular facets on spur ends; (d) multiple, nearly right-angled offsettings of stream courses; and (e) the presence of water and wind gaps along ridge crests. Moreover, poor correlation between rock strength and topographic forms, tilting of ridges in opposition to the regional slope, and relative recency of tectonic movements indicate that the ridges are fault blocks rather than having formed as a result of differential erosion along faults.

(2) Tectonic movements seriously disrupted preexisting drainage patterns, as evidenced by the persistence of a substantially lower drainage density in the western and central

parts than in the eastern part of the Piedmont Province. On the other hand, tectonic movements appear to have been continual rather than episodic in nature, as demonstrated by the absence of terraces from the steep-sided walls of antecedent stream valleys and the lack of knickpoints along the longitudinal profiles of antecedent streams.

(3) Episodes of increased fluvial aggradation following tectonic movements led to the formation of two small alluvial plains between tilted fault-block ridges I and II in the northcentral part of the Piedmont Province. These landforms effectively conceal large segments of the fault system along the front scarp of tilted fault-block ridge II in this part of the Piedmont Province.

(4) Rapid mass flowages in the form of lahars played an important role in the formation of alluvial/laharic fans in the southwestern, southcentral, and eastcentral parts of the Piedmont Province. Although magnitude and frequency of laharic events varied on individual fans, the following effects of episodic laharic deposition on fan development are noted: (a) extensive vertical as well as horizontal build-up of fan surfaces; (b) changes in the horizontal size-gradation of fan sediments by transport of large boulders for appreciable distances downslope; (c) changes in slope characteristics of fan surfaces because of abrupt breaks created along the lateral and distal margins of lahars; and (d) increase in the frequency of occurrence of large-scale stream diversions, such as those which took place along the

Río Aguas Zarcas and the Río La Vieja.

(5) The eastern part of the Piedmont Province experienced several episodes of pyroclastic deposition, including four in the southern part and between one and three in the northern part of this area. Because of the fragmentary knowledge about the spatial distribution of individual pyroclastic units and a lack of recorded data on prevailing wind directions, source areas for the differing pyroclastic deposits are uncertain. The location of the four cinder cones in the eastern part and that of a fifth cinder cone on the lower, northeastern portion of the Aguas Zarcas fan in the eastcentral part of the Piedmont Province appears to be random. In contrast, the four remaining cinder cones on the Aguas Zarcas fan are aligned along a major north-south fault.

Major landform types in southern San Carlos show a distinct spatial segregation, especially in the Piedmont Province, where tectonic, alluvial/laharic, and volcanic landforms dominate different parts of the landscape. In the Atlantic Lowland Province of the study area, spatial segregation of differing landform types is less pronounced since laharic and alluvial landforms show a nearly ubiquitous distribution in contrast to paired terraces, which are spatially more segregated than the other two landforms. Because of the disjunct spatial distribution of a large number of landforms in southern San Carlos, relative landform ages cannot be assessed for the region as a whole.

Moreover, the magnitude of age differences between landforms cannot be inferred from spatial relationships between landforms. Relative ages of landforms which can be deduced from geomorphic evidence are stated below.

In the Atlantic Lowland Province of southern San Carlos, small hills of laharic origin are the oldest and low-level paired terraces which occur at and below the surfaces of alluvial plains adjacent to present-day stream courses are the youngest landforms. Alluvial plains in this area are intermediate in age between the other two landforms. In the Piedmont Province of southern San Carlos, tilted fault-block ridges, associated with radiocarbon dates of greater than 40,000 years, antedate both the alluvial/laharic fans and the alluvial plains in this area. On the other hand, all three landforms are younger than the laharic landforms in the Atlantic Lowland Province of the study area. The five cinder cones in the eastcentral part of the Piedmont Province of southern San Carlos are older than surrounding surface deposits on the Aguas Zarcas fan. The four westernmost of these cinder cones probably have similar ages because of tectonic alignment. Surface deposits on the Aguas Zarcas as on the other alluvial/laharic fans in the Piedmont Province of the study area are older than surface deposits on the alluvial plains in the Atlantic Lowland Province of southern San Carlos. Paired terraces along the lowland reach of the Río Kopper in the latter part of the study area are younger than laharic surface deposits on the eastern portion of the La Marina fan, provided that these terraces resulted from stream adjustments of the Río Aguas Zarcas in response to laharic deposition on this fan. Both upper portions of alluvial plains and paired terraces in the Atlantic Lowland Province of southern San Carlos are younger than the cinder cones in the eastcentral part of the Piedmont Province of the study area.

Results from Soil Studies

In southern San Carlos, degree of soil development can be used as a qualitative measure of soil age because duration of soil formation has exerted the greatest influence on pedogenesis among the five major soil-forming factors. Both the regional climate and the natural vegetation show relatively small variations throughout the study area and therefore can be considered constant. Variations in parent materials, although believed to have had some effect on pedogenesis at the onset of soil formation, are considered to have lost in importance with the passage of time because of the extremely rapid rate of weathering in the hot and humid climate of the study area. Variations in topography, although responsible for some differences in pedogenic properties among the soils in the study area, generally have been of lesser importance than variations in duration of soil formation.

Differences in degree of soil development can be determined on the basis of differences in pedogenic properties for both modern and buried soils in southern San Carlos. In general, but especially in paleosols, subsoil characteristics are more highly indicative of relative degree of soil development than properties of soil-surface horizons. Moreover, relationships between pedogenic properties and relative degree of soil development are clearer in modern than in buried soils.

Of the five pedogenic properties employed, silt/clay ratios and soil texture are the most sensitive indicators of relative soil ages in both modern and buried soils. Differences in silt/clay ratios of soils provide a slightly better measure of relative soil ages than differences in soil texture. On the basis of differences in either one of these two pedogenic properties, soils at an early stage, at an intermediate stage, and at an advanced stage of soil development can be recognized. Moreover, individual soil groups can be ranked within these broad age categories. Free iron-oxide content, soil color, and illuvial-clay content allow fewer age distinctions between both modern and buried soils than the other two pedogenic properties. On the basis of differences in free iron-oxide content, modern and buried soils at an early stage, at an intermediate stage, and at an advanced stage of soil development are recognizable. On the basis of differences in soil color and illuvial-clay content, only two categories of soil development can be established. Age distinctions between individual soil groups within the broad age categories determined on the basis of differences in the latter three pedogenic properties can sometimes, but not generally, be made.

On the basis of differences in overall soil characteristics, seven modern soil groups of successively greater ages can be distinguished in southern San Carlos. These include: (1) modern soils on Loma Buenos Aires and in the area east of the cinder cone in the southeastern part of the Piedmont Province; (2) modern soils on alluvial plains in the Atlantic Lowland Province; (3) modern soils on alluvial/laharic fans in the southcentral part of the Piedmont Province; (4) modern soils on pyroclastic deposits in the vicinity of La Josefina in the northeastern part of the Piedmont Province; (5) modern soils on tilted fault-block ridges in the northwestern, northcentral, and central parts of the Piedmont Province; (6) modern soils on small hills of laharic origin in the Atlantic Lowland Province; and (7) modern soils on the cinder cone Cerro Los Chiles in the eastcentral part of the Piedmont Province. Modern soils in the first two soil groups are at an early stage, those in the next three soil groups at an intermediate stage, and those in the last two soil groups at an advanced stage of soil development. On the basis of differences in silt/clay ratios of subsoil horizons, the parent materials of modern soils in the three broad categories of soil development are considered to be Recent, Pleistocene, and Pliocene in age, respectively.

The paleosols in southern San Carlos can be divided into four different age groups on the basis of differences in overall soil characteristics. Listed in order of increasing soil age, these include: (1) a buried soil on the alluvial plain in the eastern part of the Atlantic Lowland Province; (2) buried soils on pyroclastic parent materials in the vicinity of La Josefina and on Loma Buenos Aires in the eastern part of the Piedmont Province; (3) buried soils on tilted fault-block ridges in the northwestern, north-central, and central parts of the Piedmont Province; and (4) a buried soil on one of the small hills of laharic origin in the western part of the Atlantic Lowland Province. The first of these paleosols is at an early stage and the last one at an advanced stage of soil development. On the basis of differences in silt/clay ratios of subsoil horizons, the parent materials of the two paleosols are considered to be Recent and Pliocene in age, respectively. The remaining paleosols are at an intermediate stage of soil development. The two younger of these paleosols show a similar degree of soil development and therefore are placed into the same age group. The nature of silt/clay ratios in subsoil horizons implies that the parent materials of the paleosols in the intermediate category of soil development date from the Pleistocene Epoch.

Both the modern and the buried soils in southern San Carlos show a distinct regional distribution pattern with regard to the two physiographic provinces of the study area.

In the Atlantic Lowland Province of southern San Carlos, modern as well as buried soils are either at an early or at an advanced stage of soil development, with the exception of one modern soil, which is at an intermediate stage of soil development. In the Piedmont Province of southern San Carlos, all but two modern soils, which are at an early and at an advanced stage of soil development, respectively, and all buried soils are at an intermediate stage of soil development. The temporal distribution of modern and buried soils in the study area indicates more clearly than the spatial distribution of landforms in southern San Carlos that episodes of landscape instability have varied in number and have occurred at different times in different parts of the region. Information which can be obtained from the soil data about the temporal distribution of landforms in southern San Carlos is provided below.

Pedogenesis and Landform Ages

The study of soils greatly enhanced previous knowledge, gained from geomorphic evidence, about the temporal distribution of landforms in southern San Carlos by (1) permitting an assessment of age relationships between spatially disjunct landforms and by (2) providing a better understanding of the magnitude of age differences between landforms. As a result, relative ages of most landforms in the study area can be determined. Specific information which can be obtained from the soil data follows.

(1) In the Atlantic Lowland Province of southern San Carlos, major landform types could be ranked by age on the basis of geomorphic evidence. Moreover, some indication of the magnitude of the age difference between laharic and alluvial landforms could be gained. Small hills of laharic origin were found to antedate the oldest landforms in the western and central parts of the adjacent Piedmont Province of the region. In contrast, upper portions of alluvial plains postdate the youngest landforms in these parts of the study area. The true magnitude of the age difference between the two differing landform types in the Atlantic Lowland Province is revealed by the soil data. Most modern and one buried soil on the small hills of lahric origin are at an advanced stage of soil development and considered to date from the Pliocene Epoch, indicating that the laharic landforms are of considerable antiquity. In contrast, both modern soils and underlying paleosols on the alluvial plains are at an early stage of soil development and Recent in age, indicating that alluvial deposition which created the upper portions of these landforms occurred much later than laharic deposition.

(2) Tilted fault-block ridges, which are the oldest landforms in the western and central parts of the Piedmont Province of southern San Carlos and associated with radiocarbon dates of greater than 40,000 years, are considered to have formed during the earlier part of the Pleistocene Epoch. Modern and buried soils on these landforms are

at an intermediate stage of soil development but do not exhibit a drastically lower degree of soil development than the soils on laharic landforms in the Atlantic Lowland Province of the study area. As pointed out above, the parent materials of the latter soils are believed to date from the Pliocene Epoch.

(3) On the basis of geomorphic evidence, tilted fault-block ridges were judged to be older than alluvial/laharic fans and alluvial plains in the western and central parts of the Piedmont Province. However, information about the magnitude of age differences between the differing landform types could not be obtained. The soil data indicate that both the tectonic and the alluvial/laharic landforms are Pleistocene in age. They also show that tilted fault-block ridges are appreciably older than upper portions of alluvial/laharic fans. Although modern soils on both landform types are at an intermediate stage of soil development, those on tilted fault-block ridges show a substantially higher degree of soil development than modern soils on alluvial/laharic fans. Upper portions of alluvial/laharic fans probably formed during the later part of the Pleistocene Epoch, considering that modern soils on these landforms are at a more advanced stage of soil development than soils an alluvial plains in the Atlantic Lowland Province, the next younger soils in the study area, which are considered to be at an early stage of soil development and Recent in age.

(4) On the basis of pedogenic evidence, the four westernmost cinder cones on the Aguas Zarcas fan in the eastcentral part of the Piedmont Province of southern San Carlos are considered to be the oldest landforms in the study area. Modern soils on Cerro Los Chiles, the northernmost of these tectonically aligned cinder cones, are at an advanced stage of soil development and exhibit a slightly higher degree of soil development than modern soils on small hills of laharic origin in the Atlantic Lowland Province of southern San Carlos. As the latter, modern soils on the volcanic landforms are believed to date from the Pliocene Epoch. The information which is provided by the soil data greatly exceeds that obtained from geomorphic evidence, on the basis of which it was merely known that the cinder cones are older than surrounding surface deposits on the Aguas Zarcas fan. Pedogenic evidence not only confirms that the formation of cinder cones predates the latest episodes of alluvial and laharic deposition on this fan but also indicates that the cinder cones are older than the tectonic landforms in the Piedmont Province and older than, or possibly of the same age as, the laharic landforms in the Atlantic Lowland Province of the study area.

(5) The temporal distribution of landforms in southern San Carlos could not be determined for the region as a whole mainly because age relationships between different volcanic landforms and age relationships between volcanic and other landforms in the study area could not be assessed from geo-

morphic evidence due to the disjunct spatial distribution of these landforms. On the basis of pedogenic evidence, the information gap can be narrowed.

(a) Although the source area for the pyroclastic surface deposits in the northeastern part of the Piedmont Province of southern San Carlos is unknown, the soil data indicate that the volcanic event which led to the deposition of these materials occurred at a later time than the formation of the four westernmost cinder cones in the eastcentral part of the Piedmont Province. Modern soils on the pyroclastic surface deposits in the northeastern part of the Piedmont Province are at an intermediate stage of soil development, compared to the advanced stage of soil development exhibited by modern soils on the cinder cones. The soil data also show that deposition of pyroclastic surface materials in the northeastern part of the Piedmont Province occurred after the formation of tilted fault-block ridges, but prior to the addition of surface deposits on alluvial/laharic fans in the western and central parts of the Piedmont Province. Although modern soils on the pyroclastic parent materials are at the same stage of soil development as modern soils on the other two landforms, they exhibit a lower degree of soil development than modern soils on the tectonic landforms and a higher degree of soil development than modern soils on the alluvial/laharic landforms. Since tilted fault-block ridges are believed to be early Pleistocene and upper portions of alluvial/laharic fans late Pleistocene in age, the latest episode of pyroclastic deposition in the northeastern part of the Piedmont Province probably took place during the middle part of the Pleistocene Epoch.

(b) The pyroclastic surface deposits on Loma Buenos Aires and in the area east of the cinder cone in the southeastern part of the Piedmont Province of southern San Carlos were laid down much later than pyroclastic surface deposits in the northeastern part of the Piedmont Province. Modern soils on the pyroclastic parent materials in the former area are at an early stage of soil development, compared to the intermediate stage of soil development exhibited by modern soils on the pyroclastic parent materials in the northeastern part of the Piedmont Province. The latest episode of pyroclastic deposition in the southeastern part of the Piedmont Province is believed to have taken place during the Holocene Epoch after cessation of alluvial deposition in the Atlantic Lowland Province, since modern soils on the pyroclastic parent materials are at the same stage of soil development as, but show a lower degree of soil development than, modern soils on alluvial plains in the latter part of the study area. As previously discussed, alluvial surface deposits in the Atlantic Lowland Province are considered to be Recent in age.

(c) Buried soils present in pyroclastic subsurface deposits in the northeastern and southeastern parts of the Piedmont Province show a similar degree of soil development and are considered to date from the Pleistocene Epoch. On the other hand, overlying modern soils in the two areas are at different stages of soil development and have different ages. As stated above, modern soils in the northeastern part of the Piedmont Province are at an intermediate stage of soil development and believed to be middle Pleistocene in age. In contrast, modern soils in the southeastern part of the Piedmont Province are at an early stage of soil development and considered to be Recent in age. In order to explain the similar degree of soil development exhibited by the buried soils, distinct differences in the texture of parent materials of the two paleosols must be assumed. Alternatively, if the texture of respective parent materials was similar, deposition of pyroclastic subsurface materials in the southeastern part of the Piedmont Province must have occurred at a later time than that of pyroclastic subsurface materials in the northeastern part of the area. Despite similarity in degree of soil development of paleosols, the soil data suggest that deposition of pyroclastic subsurface materials in the two areas probably resulted from two different volcanic events.

Landscape Evolution in Southern San Carlos

The present study demonstrates that major landform types in southern San Carlos have distinctly different ages. Landscape evolution in the area appears to have started as early as the Pliocene and to have continued until the recent past. Episodes of landscape instability which led to the formation of the differing landform types in the area were caused by tectonic, volcanic, fluvial, and mass-wasting events. Moreover, unstable periods varied in both kind and number and occurred at different times in different parts of the region. On the basis of geomorphic and pedogenic evidence, major episodes of landscape evolution in southern San Carlos can be summarized as follows.

(1) The earliest recorded episodes of landscape instability in southern San Carlos were caused by tectonism and resultant volcanic activity and laharic deposition. Faulting and explosive volcanic activity led to the formation of four cinder cones in the eastcentral part of the Piedmont Province of the region. Faulting, occurring on the summits and upper slopes of two strato-volcanoes, Volcán Viejo and Cerro Porvenir, in the Mountainous Province of San Carlos, triggered the formation of massive lahars, which came to rest beyond the foot the the volcanoes in the Atlantic Lowland Province of the study area, where they formed a hummocky topography with small hills and intervening shallow depressions. On the basis of geomorphic and pedogenic evidence, both episodes of landscape

instability are believed to have occurred during the Pliocene Epoch. Moreover, the soil data indicate that formation of the volcanic landforms in the eastcentral part of the Piedmont Province and of the laharic landforms in the Atlantic Lowland Province probably took place at approximately the same time.

(2) The next major episode of landscape instability in southern San Carlos was caused by faulting and uplift associated with tilting, leading to the formation of three tilted fault-block ridges in the northwestern, northcentral, and central parts of the Piedmont Province of the study area. Pedogenic evidence indicates that this episode of landscape instability occurred during the earlier part of the Pleistocene Epoch. Supporting evidence is provided by three radiocarbon dates, obtained on wood samples collected near the base of the backslope of tilted fault-block ridge II, which show that the tectonic landforms are older than 40,000 years.

(3) The formation of tilted fault-block ridges resulted in major changes in the preexisting drainage pattern in the western and central parts of the Piedmont Province of southern San Carlos, causing multiple, nearly right-angled offsettings of larger and serious disruption of smaller stream courses. It also led to several successive episodes of increased fluvial aggradation in this part and in the Atlantic Lowland Province of the study area. The latter events caused the formation of two small alluvial

plains between tilted fault-block ridges I and II in the northcentral part of the Piedmont Province and, aided greatly by intermittent laharic deposition, created several alluvial/laharic fans in the southwestern and southcentral parts of the Piedmont Province. Another alluvial/laharic fan in the eastcentral part of the Piedmont Province is believed to have formed at approximately the same time. In the Atlantic Lowland Province of the study area, the buildup of alluvial plains was initiated because streams in this area carried an increased load of sediments, resulting from accelerated erosion in their upper reaches in response to steepening of stream gradients caused by tectonic uplift and resultant formation of alluvial/laharic fans. Although alluvial/laharic and alluvial landforms in the two physiographic provinces of the study area started to form shortly after the creation of tilted fault-block ridges, surface deposits on the differing landforms were laid down at later and different times. On the basis of pedogenic evidence, upper portions of alluvial/laharic fans in the Piedmont Province are believed to date from the later part of the Pleistocene Epoch. In contrast, upper portions of alluvial plains in the Atlantic Lowland Province are considered to be Recent in age.

(4) Several episodes of landscape instability, resulting from intermittent explosive volcanic activity, are documented in the eastern part of the Piedmont Province of southern San Carlos. In the northern part of this area,

the number of exposed pyroclastic units decreases from three in the west to one in the east, as the thickness of the surface unit increases. In the southern part of the area, four different pyroclastic units are recognizable. Pedogenic evidence indicates that the two latest episodes of pyroclastic deposition in both the northeastern and southeastern parts of the Piedmont Province took place after formation of the four westernmost cinder cones in the eastcentral part of the Piedmont Province. Moreover, although occurring at different times in the northern and southern parts of the area, the most recent episodes of explosive volcanic activity in the eastern part of the Piedmont Province postdate the formation of tilted fault-block ridges in the western and central parts of the Piedmont Province. On the basis of pedogenic evidence, pyroclastic surface deposits in the northeastern part of the Piedmont Province are believed to date from the middle part of the Pleistocene Epoch and therefore are older than upper portions of alluvial/laharic and alluvial landforms in the two physiographic provinces of the study area. In contrast, pyroclastic surface deposits in the southeastern part of the Piedmont Province are considered to be Recent in age and to be younger than upper portions of alluvial plains in the Atlantic Lowland Province of the study area.

(5) The latest episode of explosive volcanic activity in the eastern part of the Piedmont Province of southern possibly took place at the time when increased fluvial

aggradation in the Atlantic Lowland Province of the study area was succeeded by closely spaced episodes of increased fluvial degradation, which led to the formation of low-level paired terraces along present-day streams. The formation of two paired terraces along the lowland reach of the Río Kopper probably resulted from successive channel adjustments of the Río Aguas Zarcas in response to laharic deposition on the eastern portion of the La Marina fan. On the basis of geomorphic evidence, the latter events are considered to represent the most recent episodes of landscape instability in the Atlantic Lowland Province of southern San Carlos.

LIST OF REFERENCES

AID Resource Inventory Center, Corps of Engineers, U.S. Army, 1965, Costa Rica: Analisis regional de recursos físicos (Regional analysis of physical resources): Washington, D.C., 33 p.

Bigarella, J. J., and Andrade, G. O., 1965, Contributions to the study of the Brazilian Quaternary, in Wright, H. E., Jr., and Frey, D. G., eds., International studies on the Quaternary: Geol. Soc. America Spec. Paper 84, p. 433-451.

Birkeland, P. W., 1974, Pedology, weathering, and geomorphological research: New York, Oxford Univ. Press, 285 p.

Blake, G. R., 1965, Bulk density, in Black, C. A., ed., Methods of soil analysis: Agronomy, no. 9, pt. 1, p. 374-390.

Buckman, H. O., and Brady, N. C., 1969, The nature and properties of soils: New York, The Macmillan Co., 653 p.

Büdel, J., 1950, Das System der klimatischen Morphologie: München, Deutscher Geographentag 1948, p. 65-100.

________ 1963, Klima-genetische Geomorphologie: Geol. Rundschau, v. 15, no. 7, p. 269-285.

Bull, W. B., 1964, Alluvial fans and near-surface subsidence in western Fresno County, California: U.S. Geol. Survey Prof. Paper 437-A, 71 p.

Buol, S. W., Hole, F. D., and McCracken, R. J., 1973, Soil genesis and classification: Ames, The Iowa State Univ. Press, 360 p.

Butler, B. E., 1959, Periodic phenomena in landscapes as a basis for soil studies: C.S.I.R.O. Aust. Soil Publ. No. 14, 20 p.

Caspall, F. C., 1970, The spatial and temporal variations in loess deposition in northeastern Kansas: Ph.D. dissertation, Univ. of Kansas, 294 p.

CLIMAP Project Members, 1976, The surface of the ice-age earth: Science, v. 191, no. 4232, p. 1131-1137.

Crandell, D. R., 1968, Mudflow, in Fairbridge, R. W., ed., The encyclopedia of geomorphology: New York, Reinholt Corp., p. 763-764.

________ 1971, Postglacial lahars from Mount Rainier Volcano, Washington: U.S. Geol. Survey Prof. Paper 677, 75 p.

Damuth, J. E., and Fairbridge, R. W., 1970, Equatorial Atlantic deep-sea arkosic sands and ice-age aridity in tropical South America: Geol. Soc. America Bull., v. 81, p. 189-206.

Day, P. R., 1965, Particle fractionation and particle-size analysis, in Black, C. A., ed., Methods of soil analysis: Agronomy, no. 9, pt. 1, p. 545-567.

D'Hoore, J., 1960, The soils map of Africa south of the Sahara (1:5,000,000): Madison, Trans. Int. Congr. Soil Sci., Congr. VII, v. 4, p. 11-19.

Flint, R. F., 1971, Glacial and Quaternary geology: New York, John Wiley and Sons, Inc., 892 p.

Flohn, H., 1952, Allgemeine atmosphärische Zirkulation und Paläoklimatologie: Geol. Rundschau, v. 40, no. 1, p. 153-178.

________ 1953, Studien über die atmosphärische Zirkulation in der letzten Eiszeit: Erdkunde, v. 7, no. 4, p. 266-275.

Galloway, R. W., 1965, A note on world precipitation during the last glaciation: Eiszeitalter und Gegenwart, v. 16, p. 76-77.

Gardner, W. H., 1965, Water content, in Black, C. A., ed., Methods of soil analysis: Agronomy, no. 9, pt. 1, p. 82-127.

Gates, W. L., 1976, Modeling the ice-age climate: Science, v. 191, no. 4232, p. 1138-1144.

Geikie, A., 1903, Textbook of geology, v. 1: New York, The Macmillan Co., 702 p.

Haffer, J., 1969, Speciation in Amazonian forest birds: Science, v. 165, no. 3889, p. 131-137.

Harris, S., 1971, Index of structure: evaluation of a modified method of determining aggregate stability: Geoderma, v. 6, p. 155-162.

Harris, S. A., Neumann, A. M., and Stouse, P. A. D., Jr., 1971, The major soil zones of Costa Rica: Soil Sci., v. 112, no. 6, p. 439-447.

Hastenrath, S. L., 1967a, Observations on the snow line in the Peruvian Andes: Jour. Glaciol., v. 6, no. 3-4, p. 244-273.

________ 1967b, Rainfall distribution and regime in Central America: Archiv Met. Geoph. Biokl., B, v. 15, p. 201-241.

________ 1968, A contribution to the wind conditions over the Carribean Sea and Gulf of Mexico: Tellus, v. 20, p. 163-178.

________ 1971, On snow line depression and atmospheric circulation in the Tropical Americas during the Pleistocene: South African Geogr. Jour., v. 53, p. 53-69.

Instituto Geográfico Nacional, 1966a, Costa Rica 1:50,000, San Lorenzo, Hoja 3246 I: San José.

________ 1966b, Costa Rica 1:50,000, Fortuna, Hoja 3247 II: San José.

________ 1966c, Costa Rica 1:50,000, Quesada, Hoja 3346 IV: San José.

________ 1966d, Costa Rica 1:50,000, Río Cuarto, Hoja 3347 II: San José.

________ 1966e, Costa Rica 1:50,000, Tres Amigos, Hoja 3347 IV: San José.

________ 1967, Costa Rica 1:50,000, A uas Zarcas, Hoja 3347 III: San José.

Jenny, H., 1941, Factors of soil formation: New York, McGraw-Hill, 281 p.

Kilmer, V. J., and Alexander, L. T., 1949, Methods of making mechanical analysis of soils: Soil Sci., v. 68, p. 15-24.

Leopold, L. B., Wolman, M. G., and Miller, J. P., 1964, Fluvial processes in geomorphology: San Francisco, W. H. Freeman and Co., 522 p.

Lindsay, J. F., 1968, The development of clast fabric in mudflows: Jour. Sed. Petrol., v. 38, p. 1242-1253.

Malavassi V., E., 1966a, Geología, *in* Sandner, G., Nuhn, H., et al., Estudio geográfico regional de la Zona Norte de Costa Rica: San José, Instituto de Tierras y Colonización (ITCO), p. 21-31.

________ 1966b, Geología, *in* Sandner, G., Nuhn, H., et al., Estudio geográfico regional de la Zona Norte de Costa Rica: San José, ITCO, map 6.

Ministerio de Agricultura y Ganadería, 1970, Lluvia: resúmen de la década 1960-1969: San José, Servicio Meteorológico, 83 p.

Ministerio de Industria y Comercio, 1968, Mapa geológico de Costa Rica (1:700,000): San José, Dirección de Geología, Minas y Petróleo.

Mullineaux, D. R., and Crandell, D. R., 1962, Recent lahars from Mount St. Helens, Washington: Geol. Soc. America Bull., v. 73, no. 7, p. 855-869.

Nuhn, H., 1966, Clima, *in* Sandner, G., Nuhn, H., et al., Estudio geográfico regional de la Zona Norte de Costa Rica: San José, ITCO, p. 32-46.

Olson, R. V., 1965, Iron, *in* Black, C. A., ed., Methods of soil analysis: Agronomy, no. 9, pt. 2, p. 963-973.

Peech, M., 1965, Exchange acidity, *in* Black, C. A., ed., Methods of soil analysis: Agronomy, no. 9, pt. 2, p. 914-926.

Peltier, L. C., 1950, The geographic cycle in periglacial regions as it is related to climatic geography: Ann. Assoc. Am. Geogr., v. 40, p. 214-236.

Pérez, S., 1966, Vegetación, *in* Sandner, G., Nuhn, H., et al., Estudio geográfico regional de la Zona Norte de Costa Rica: San José, ITCO, map 10.

________, and Chacón A., F., 1966, Vegetación, *in* Sandner, G., Nuhn, H., et al., Estudio geográfico regional de la Zona Norte de Costa Rica: San José, ITCO, p. 88-112.

Sandner, G., 1966a, Orografía y tipos de relieve, *in* Sandner, G., Nuhn, H., et al., Estudio geográfico regional de la Zona Norte de Costa Rica: San José, ITCO, p. 12-20.

________ 1966b, Tipos de relieve, in Sandner, G., Nuhn, H., et al., Estudio geográfico regional de la Zona Norte de Costa Rica: San José, ITCO, map 5.

Sapper, K., 1932, Klimakunde von Mittelamerika, in Köppen, W., and Geiger, R., eds., Handbuch der Klimatologie, v. 2, pt. H: Berlin, Gebrüder Borntraeger, 74 p.

Soil Survey Staff, 1951, Soil survey manual: Washington, D.C., U.S. Dept. Agr. Handbook No. 18, 503 p.

________ 1960, Soil classification, a comprehensive system (7th approximation): Washington, D.C., U.S. Dept. Agr., Soil Conserv. Serv., 265 p.

Sombroek, W. G., 1966, Amazon soils: Wageningen, Centre for Agricultural Publications and Documentation, 292 p.

Thornbury, W. D., 1969, Principles of geomorphology: New York, John Wiley and Sons, Inc., 594 p.

Tosi, J. A., Jr., 1964, Climatic control of terrestrial ecosystems: a report on the Holdridge model: Econ. Geogr., v. 40, p. 173-181.

Troll, C., 1959, Die tropischen Gebirge. Ihre dreidimensionale klimatische und pflanzengeographische Zonierung: Bonner Geogr. Abh., Heft 25, 93 p.

Van Wambeke, A. R., 1962, Criteria for classifying tropical soils by age: Jour. Soil Sci., v. 13, no. 1, p. 124-132.

Vuilleumier, B. S., 1971, Pleistocene changes in the fauna and flora of South America: Science, v. 173, no. 3999, p. 771-780.

Weyl, R., 1956a, Eiszeitliche Gletscherspuren in Costa Rica (Mittelamerika): Zeitschr. f. Gletscherkunde, v. 3, p. 317-325.

________ 1956b, Spuren eiszeitlicher Vergletscherung in der Cordillera de Talamanca Costa Ricas (Mittelamerika): Neues Jb. Geol. u. Paläont. Abh., v. 102, p. 283-294.

________ 1961, Die Geologie Mittelamerikas: Berlin, Gebrüder Borntraeger, 226 p.

Wilhelmy, H. C., 1950, Eiszeit und Eiszeitklima in den feuchttropischen Anden: Peterm. Geogr. Mitt., Ergänzungsheft 262, p. 281-310.

Willet, H. C., 1950, The general circulation at the last (Würm) glacial maximum: Geogr. Annaler, v. 32, p. 179-187.

________, and Sanders, F., 1959, Descriptive meteorology: New York, Academic Press, 355 p.

APPENDIX I

SOIL PROFILE DESCRIPTIONS

In the field, both soil profiles and individual soil samples were numbered in the order in which they were described and sampled. In the appendix, soil profile descriptions are presented by physiographic province and landform type for easier reference. Descriptions of soil profiles at sampling sites 25 and 27 are omitted because the data were not used in the present study.

The location of sampling sites is given to the nearest 100 m, using the UTM (Universal Transverse Mercator) grid system. All soil colors are for moist conditions. Soil textures given in the descriptions are those obtained by particle-size analysis in the laboratory. Horizon designations are based on both field observations and laboratory analyses.

Soils on Small Hills of Laharic Origin in the Atlantic Lowland Province

Soil Profile 2

Location: 0.5 km southeast of the Hacienda Altamira

The site is located in the eastern part of the Atlantic Lowland Province on the west side of the road which connects the Haciendas Altamirita (Los Llanos) and Altamira. It is situated in the central portion of a road cut through the second subdued hill north of the Hacienda Altamirita. The hills in this area rise only slightly above the floodplain of the Río Aguas Zarcas, but are very conspicuous due to the reddish soils by which they are covered.

Map Reference: Aguas Zarcas (1:50,000) 957753

Elevation: 65 m Slope: 2° Aspect: East

Drainage: Moderately good Vegetation: Pasture

Parent Material: Laharic deposits

Horizon and Sample No.	Depth (cm.)	Description
A1 (QU 13)	0-15	Dark reddish brown (5YR 3/3) clay loam; well developed very fine to fine subangular blocky structure; moist, fairly friable; sticky when wet; roots very abundant; earthworms present; abrupt smooth boundary.
B1 (QU 14)	15-35	Dark reddish brown (5YR 3/3) clay; well developed fine subangular blocky structure; moist, fairly friable; sticky when wet; roots less abundant than in horizon above; gradual smooth boundary.
B21 (QU 15)	35-60	Dark red (2.5YR 3.5/6) clay; weakly developed fine subangular blocky structure; fairly moist, fairly friable; sticky when wet; roots present; diffuse smooth boundary.
B22t (QU 16)	60-98	Dark red (2.5YR 3/6) clay; well developed fine subangular to angular blocky structure; clay skins present; fairly moist, fairly friable; sticky when wet but less so than in horizon above; roots present; diffuse smooth boundary.
B23t (QU 17)	98-125+	Dark reddish brown (5YR 3/4) clay; well developed medium subangular to angular blocky structure; clay skins very abundant; fairly moist, fairly firm; sticky when wet; a few roots present.

Soil Profile 10

Location: 2.6 km north of San Francisco

The site is located in the central part of the Atlantic Lowland Province on one of the subdued hills which rise above the floodplain of the Río Kopper in the vicinity of the Finca Alpízar Castro.

Map Reference: Aguas Zarcas (1:50,000) 920721

Elevation: 80 m   Slope: 2°   Aspect: Northwest

Drainage: Moderately good   Vegetation: Pasture

Parent Material: Laharic deposits

Horizon and Sample No.	Depth (cm.)	Description
Ap (QU 71)	0-13	Dark reddish brown (5YR 3/4) sandy clay loam; well developed fine subangular blocky structure; a few weakly developed clay skins present; fairly dry, fairly friable; roots very abundant; clear smooth boundary.
B1t (QU 72)	13-28	Dark reddish brown (5YR 3/3) clay; well developed fine subangular blocky structure; a few weakly developed clay skins present; fairly dry, fairly friable; roots abundant; clear smooth boundary.
B21t (QU 73)	28-50	Dark red (2.5YR 3/6) clay; well developed very fine to fine subangular blocky structure; many weakly and a few well developed clay skins present; fairly dry, fairly friable; a few roots present; gradual smooth boundary.
B22t (QU 74)	50-68	Dark reddish brown to dark red (2.5YR 3/5) clay; well developed very fine to fine subangular blocky structure; many well developed clay skins present; fairly moist, fairly friable; a few roots present; gradual smooth boundary.
B23t (QU 75)	68-80+	Dark reddish brown to dark red (2.5YR 3/5) clay; well developed very fine to fine angular blocky structure; many well developed clay skins present; fairly moist, fairly friable.

Soil Profile 21

Location: 0.2 km south of Muelle San Carlos

The site is located in the western part of the Atlantic Lowland Province on the south side of the road that leads into Muelle San Carlos from Platanar. This is the first locality at which laharic deposits crop out along the road after it has descended the front scarp of tilted fault-block ridge I. Two soils, a surface and a buried soil, are recognized at the site. Big, partially decomposed boulders are present in the buried soil.

Map Reference: Aguas Zarcas (1:50,000) 857726

Elevation: 65 m Slope: ? Aspect: North

Drainage: Good Vegetation: Pasture

Parent Material: Laharic deposits

Horizon and Sample No.	Depth (cm.)	Description
A1 (QU145)	0-13	Dark reddish brown (5YR 3/2.5) clay loam; weakly developed very fine subangular blocky structure; moist, fairly friable; many roots present; many earthworms, earthworm casts, and ants present; clear smooth boundary.
B21t (QU146)	13-25	Dark reddish brown to dark red (2.5YR 3/5) clay; well developed fine and weakly developed very fine subangular blocky structure; well developed clay skins present; moist, fairly friable; many roots presents; clear smooth boundary.
B22 (QU147)	25-55	Dark red (2.5YR 3/6) clay; weakly developed very fine subangular blocky structure; moist, friable; roots present; pieces of decomposing bedrock present; gradual smooth boundary.
B23 (QU148)	55-75	Dusky red to dark reddish brown (2.5YR 3/3) clay; well developed fine subangular blocky structure; moist, friable; roots present; pieces of decomposing bedrock present; abrupt smooth boundary.
IIA1b (QU149)	75-90	Dark reddish brown (5YR 3/3) clay; well developed fine angular blocky structure; moist, fairly friable; some roots present; clear smooth boundary.

Horizon and Sample No.	Depth (cm.)	Description
IIB21tb (QU150)	90-100	Dark red to red (2.5YR 3.5/6) clay; well developed fine angular blocky structure; weakly developed and a few well developed clay skins present; moist, friable; clear smooth boundary.
IIB22tb (QU151)	100-155	Dark red (2.5YR 3/6) clay; well developed fine to medium angular blocky structure; many well developed clay skins present; moist, friable; gradual smooth boundary.
IIB23tb (QU152)	155-203	Red (2.5YR 4/6) clay; well developed fine to medium angular blocky structure; many well developed clay skins present; moist, friable; yellowish red (5YR 5/6 and 5YR 5/8) mottles present; gradual smooth boundary.
IIB24tb (QU153)	203-263	Red (2.5YR 4/6) clay; well developed fine to medium angular blocky structure; many very well developed clay skins present; moist, fairly firm; yellowish red (5YR 5/6) mottles present in greater number than in horizon above; pieces of decomposing bedrock present; gradual smooth boundary.
IIB25tb (QU154)	263-338+	Red (2.5YR 4/7) clay; well developed fine to medium angular blocky structure; many well developed clay skins present; moist, fairly firm; strong brown (7.5YR 5/6) and light brownish gray (10YR 6/2) mottles present in greater number than in horizon above; in the center of the section big, partially decomposed boulders present which show spheroidal weathering (one boulder with a relatively unweathered core had a weathering rind of 55 cm in thickness.

Soil Profile 28

Location: 3.1 km north of San Francisco

The site is located in the central part of the Atlantic Lowland Province approximately 100 m north of the Finca Alpízar Castro on one of the subdued hills which rise above the floodplain of the Río Kopper.

Map Reference: Aguas Zarcas (1:50,000) 923725

Elevation: 75 m Slope: 7.5° Aspect: Northeast

Drainage: Moderately good Vegetation: Pasture

Parent Material: Laharic deposits

Horizon and Sample No.	Depth (cm.)	Description
Ap (QU220)	0-23	Dark reddish brown (5YR 3/4) clay; moderate fine subangular blocky structure; a few weak clay skins present; moist, friable; many roots; earthworms and microfaunal casts and eggs common; clear smooth boundary.
B21 (QU221)	23-43	Reddish brown to red (2.5YR 4/5) clay; moderate fine to medium subangular blocky structure; moist, very friable; a few roots present; clear wavy boundary.
B22t (QU222)	43-68	Red (2.5YR 4/6) clay; strong medium subangular blocky structure; a few moderate clay skins present; moist, friable; a few faint fine yellow mottles present; clear smooth boundary.
B23t (QU223)	68-120+	Reddish brown (2.5YR 4/4) clay; compound strong medium prismatic and strong medium subangular to angular blocky structure; moderate clay skins common; moist, firm; faint medium yellow and red mottles common.

Soil Profile 29

Location: 0.9 km northeast of the Sociedad Ganederia Río Kopper

The site is located in the central part of the Atlantic Lowland Province on the southeast side of one of the larger hills which rise above the floodplain of the Río Kopper in the vicinity of the Sociedad Ganadería Río Kopper.

Map Reference: Aguas Zarcas (1:50,000) 896746

Elevation: 65 m Slope: 7.5° Aspect: East

Drainage: Moderately good Vegetation: Pasture

Parent Material: Laharic deposits

Horizon and Sample No.	Depth (cm.)	Description
A1 (QU224)	0-38	Reddish brown (5YR 4/3) clay; weak fine subangular blocky structure; moist, very friable; roots very abundant; animal casts and eggs present; gradual smooth boundary.
B21 (QU225)	38-70	Yellowish red (5YR 4/6) clay; moderate fine subangular blocky structure; moist, very friable; many roots present; gradual smooth boundary.
B22t (QU226)	70-108	Yellowish red (5YR 4/6) clay; moderate fine to medium subangular blocky structure; a few moderate clay skins present; moist, very friable; a few roots present; gradual smooth boundary.
B23t (QU227)	108-148	Yellowish red (5YR 4/6) clay; strong medium subangular to angular blocky structure; many moderate to strong clay skins present; moist, friable; gradual smooth boundary.
B24t (QU228)	148-158	Yellowish red (5YR 4/6) clay; strong fine and medium angular blocky structure; many strong clay skins present; moist, firm; a few faint fine and medium yellow mottles present; gradual smooth boundary.
B25t (QU229)	158-220	Yellowish red (5YR 4/6) clay; strong medium angular blocky structure; many strong clay skins present; slickensides common; moist, firm; medium distinct brown (10YR 5/3) mottles common; gradual smooth boundary.

Horizon and Sample No.	Depth (cm.)	Description
IIB26t (QU230)	220-255	Red (2.5YR 4/6) clay; strong coarse angular blocky structure, many strong clay skins present; slickensides common; moist, firm; many distinct coarse brown (7.5YR 5/4) and reddish brown (2.5YR 5/4) mottles present; gradual smooth boundary.
IIB27t (QU231)	255-380+	Dark red (5YR 3/6) clay; strong fine and coarse angular blocky structure; many strong clay skins present; many slickensides present; moist, very firm; many prominent coarse brownish yellow (10YR 6/6), brown (7.5YR 5/4), strong brown (7.5YR 5/1), dusky red (7.5YR 3/4), red (10YR 4/8, 2.5YR 4/6, and 2.5YR 4/8), and light gray (7.5YR 7/10) mottles present; the light gray and red mottles increase in size and abundance with depth.

Soils on Alluvial Plains in the Atlantic Lowland Province

Soil Profile 1

Location: 0.5 km southeast of the Hacienda Altamira

The site is located on a right outside bend of the Río Aguas Zarcas below a weir that diverts part of the stream flow to a small irrigation canal. At present, the river is cutting into a layer of coarse gravel. The alluvium above this layer consists of several depositional units of varying texture and thickness.

Map Reference: Aguas Zarcas (1:50,000) 958752

Elevation: 60 m Slope: 1° Aspect: West

Drainage: Moderately good Vegetation: Pasture

Parent Material: Alluvium

A1 (QU 1)	0-8	Dark brown to brown (7.5YR 4/4) sandy loam; well developed fine crumb structure; moist, friable; roots very abundant; earthworms present; in the upper part of the horizon red clay is present which has been washed down from the subdued hill on which site 2 is located; clear smooth boundary.
B1 (QU 2)	8-13	Dark brown to brown (7.5YR 4/4) sandy loam; well developed medium crumb structure; moist, friable; roots abundant; earthworms present; gradual smooth boundary.

Horizon and Sample No.	Depth (cm.)	Description
B21 (QU 3)	13-48	Dark yellowish brown (10YR 4/4) sandy loam; weakly developed very fine to fine subangular blocky structure; moist, friable; roots abundant; earthworms and other macrofauna present; the lower boundary of the horizon is marked by a stone line of small pebbles with long-axes up to 2 cm in length; gradual smooth boundary.
IIB22 (QU 4)	48-63	Dark brown to brown (7.5YR 4/4) sandy loam; well developed very fine to fine subangular blocky structure; moist, friable; roots present; gradual smooth boundary.
IIC (QU 5)	63-75	Yellowish brown (10YR 5/4) sandy loam; well developed medium subangular blocky structure; moist, friable; a few roots present; abrupt smooth boundary.
IIIA1b (QU 6)	75-88	Strong brown (7.5YR 5/6) loam; well developed medium subangular blocky structure; moist, friable; a few roots present; yellowish red (5YR 5/8) and pale red (2.5YR 6/2) mottles present; darker layer of about 2.5 cm in thickness is present on top of the mottled layer; clear slightly wavy boundary.
IIIB2b (QU 7)	88-103	Strong brown (7.5YR 5/6) silty loam; well developed fine subangular blocky structure; moist, friable; a few roots present; dark reddish brown (2.5YR 3/6) mottles present; diffuse smooth boundary.
IIIB3b (QU 8)	103-123	Strong brown (7.5YR 5/6) loam; well developed fine subangular blocky structure; moist, fairly friable; a few roots present; yellowish red (2.5YR 4/6) and yellowish brown (10YR 5/4) mottles present; clear smooth boundary.
IIIC1b (QU 9)	123-138	Strong brown (7.5YR 5/6) sandy loam; weakly developed very fine to fine subangular blocky structure; moist, friable; yellowish red (5YR 5/8) and yellowish brown (10YR 5/4) mottles present; abrupt smooth boundary.
IVC2cnb (QU10)	138-148	Strong brown (7.5YR 5/6) loamy sand; weakly developed very fine subangular blocky structure; moist, friable; intermixed with pebbles with long-axes up to 6.5 cm in length which are largest in the upper portion of the horizon; iron grains are present at the bottom of the horizon; abrupt smooth boundary.

Horizon and Sample No.	Depth (cm.)	Description
VC3b (QU11)	148-158	Strong brown (7.5YR 4/5) sandy loam; weakly developed medium subangular blocky structure; moist, friable; yellowish brown (10YR 5/4) mottles present; abrupt smooth boundary.
VIC4b (QU12)	158-203+	Gravelly sand; very few fines; no structure; largest pebbles have a long-axis up to 25 cm in length.

Soils on Tilted Fault-Block Ridge I in the Piedmont Province

Soil Profile 9

Location: 1.7 km northeast of San Franciso

The site is located on the front scarp of tilted fault-block ridge I near its eastern end. At and in the vicinity of the site large boulders are present on top and in the upper portion of the soil. The uppermost soil horizon contains well developed clay skins which indicates that the A1 horizon has been removed by erosion.

Map Reference: Aguas Zarcas (1:50,000) 933709

Elevation: 105 m Slope: 5-6° Aspect: Southeast

Drainage: Moderately good Vegetation: ?

Parent Material: Laharic deposits

Ap (QU64)	0-13	Dark reddish brown (2.5YR 2.5/4) clay; well developed fine to very fine subangular blocky structure; many well developed clay skins present; fairly moist, fairly firm; roots abundant; clear smooth boundary.
B21t (QU65)	13-28	Dark reddish brown (2.5YR 3/4) clay; well developed fine to very fine subangular blocky structure; many well developed clay skins present; moist, firm; a few roots present; clear smooth boundary.
B22t (QU66)	28-43	Dark red (2.5YR 3/6) clay; well developed fine subangular blocky structure; clay skins present but fewer than in horizon above; moist, fairly friable; some roots present; clear smooth boundary.

Horizon and Sample No.	Depth (cm.)	Description
B23 (QU67)	43-78	Dark red to red (2.5YR 3.5/6) clay; weakly developed fine angular blocky structure; moist, fairly friable; a few roots present; gradual smooth boundary.
B24 (QU68)	78-105+	Dark red (2.5YR 3/6) clay; well developed fine subangular to angular blocky structure; moist. fairly friable; a few roots present.

Soil Profile 13

Location: 0.3 km northwest of San Francisco

The site is located on the front scarp of tilted fault-block ridge I in its eastern part. It is in a cut on the south side of a footpath which branches off from the road that leads from San Francisco to the Finca Alpízar Castro. The more recent laharic surface deposits are underlain by pyroclastic materials.

Map Reference: Aguas Zarcas (1: 50,000) 921701

Elevation: 140 m Slope: ? Aspect: Northeast

Drainage: Good Vegetation: Pasture

Parent Material: Laharic deposits underlain by pyroclastic deposits

A1 (QU90)	0-15	Dark brown (7.5YR 3.5/2) loam; well developed very fine subangular blocky structure; vertical cracks present; fairly moist, fairly firm; roots very abundant; animal burrows, animal eggs, worm casts, and millipeds present; gradual smooth boundary.
B21t (QU96)	15-33	Dark reddish brown (5YR 3/4) clay; well developed very fine to fine angular blocky structure; weakly developed clay skins present throughout the horizon and well developed clay skins common along vertical cracks; moist, fairly firm; roots abundant; clear smooth boundary.
B22t (QU97)	33-50	Dark reddish brown (5YR 3/3.5) clay; well developed very fine to fine subangular blocky structure; well developed clay skins present; moist, friable; roots present; clear smooth boundary.

Horizon and Sample No.	Depth (cm.)	Description
IIB23 (QU92)	50-80	Reddish brown (5YR 4/4) clay; well developed fine subangular blocky structure; moist, friable; a few roots present; a few pieces of decomposing rock fragments present; gradual smooth boundary.
IIB24 (QU93)	80-130	Yellowish red (5YR 4/6) clay; well developed very fine to fine subangular blocky structure; moist, friable; a few roots present; many pieces of decomposing rock fragments present; clear smooth boundary.
IIB25t (QU94)	130-167	Yellowish red (5YR 4/6) clay; well developed fine subangular to angular blocky structure; a few weakly developed clay skins present; moist, fairly friable; pink, yellow, and gray mottles which are caused by decomposing rock fragments present; clear wavy boundary.
IIB3t (QU95)	167-185+	Dark red (2.5YR 3/6) clay; well developed fine angular blocky structure; a few weakly developed clay skins present; moist, fairly firm; many pieces of decomposing rock fragments and associated mottles present.

<u>Soil Profile 18</u>

Location: 0.5 km north of the center of Platanar

The site is located on the front scarp of tilted fault-block ridge I at its western end. It is on the right bank of a small creek west of the road which leads from Florencia to Muelle San Carlos.

Map Reference: Aguas Zarcas (1:50,000) 849670

Elevation: 70 m Slope: ? Aspect: South

Drainage: Moderately poor Vegetation: Pasture, but site is under a big tree which grows along the stream bank

Parent Material: Pyroclastic deposits

Ap (QU125)	0-43	Dark reddish brown (5YR 3/4) clay loam; well developed very fine subangular blocky structure; many well developed clay skins present; fairly dry, fairly friable; many roots present; many earthworms, earthworm casts, and other microfauna present; clear smooth boundary.

Horizon and Sample No.	Depth (cm.)	Description
B21t (QU126)	43-65	Reddish brown (5YR 4/4) clay; well developed very fine angular blocky structure; many well developed clay skins present; fairly moist, fairly friable; a few medium and large tree roots present; gradual smooth boundary.
B22tcn (QU127)	65-90	Yellowish red (5YR 4/6) clay; well developed fine angular blocky structure; many well developed clay skins present; manganese shot very common; moist, fairly friable; a few medium and large tree roots present; gradual smooth boundary.
B23tcn (QU128)	90-133	Red (2.5YR 4/6) clay; well developed fine to medium angular blocky structure; many well developed clay skins present; manganese shot very abundant; moist, fairly friable; a few medium and large tree roots present; many yellowish red (5YR 5/6) and strong brown (7.5YR 5.5/6) mottles present; diffuse smooth boundary.
B24t (QU129)	133-160+	Dark yellowish brown (10YR 4/8) clay; well developed fine angular blocky structure; many extremely well developed clay skins present; moist, fairly friable; brown (7.5YR 5/4) mottles present.

<u>Soil Profile 34</u>

Location: 1.2 km south of the center of Platanar

The site is located on the backslope of tilted fault-block ridge I at its western end. It is in the central portion of a cut on the west side of the road which connects Florencia with Muelle San Carlos.

Map Reference: Aguas Zarcas (1:50,000) 846656

Elevation: 75 m   Slope: 0.5°   Aspect: East

Drainage: Good   Vegetation: Coffee

Parent Material: Pyroclastic deposits

Horizon and Sample No.	Depth (cm.)	Description
A1 (QU266)	0-20	Dark yellowish brown (10YR 3/4) clay; moderate fine subangular blocky structure; fairly dry, firm; many roots present; animal casts and burrows and earthworms common; clear smooth boundary.
B1 t (QU267)	20-40	Reddish brown (5YR 4/3) clay; strong medium subangular blocky structure; a few weak clay skins present; moist, firm; many roots present; gradual smooth boundary.
B21t (QU268)	40-58	Reddish brown (5YR 4/4) clay; moderate very fine subangular blocky structure; a few weak clay skins present; moist, friable; many roots present; clear smooth boundary.
B22t (QU269)	58-88	Reddish brown (5YR 4/4) clay; moderate fine subangular blocky structure; a few weak clay skins present; moist, friable; many roots present; clear smooth boundary.
B23 (QU270)	88-120	Dark brown to brown (7.5YR 4/4) clay; moderate fine subangular blocky structure; moist, friable; roots common; gradual smooth boundary.
B24 (QU271)	120-158	Yellowish red (5YR 4.5/6) clay; strong medium subangular blocky structure; moist, friable; a few roots present; gradual smooth boundary.
IIB21tb (QU272)	158-208	Yellowish red (5YR 4/6) clay; strong fine angular blocky structure; weak clay skins common and a few moderate clay skins present; moist, friable; faint fine and medium yellowish brown (10YR 5/6) mottles common which incease in size and abundance with depth; gradual smooth boundary.
IIB22tb (QU273)	208-225	Yellowish red (5YR 5/6) clay; strong fine angular blocky structure; weak clay skins common; moist, friable; faint fine and medium yellowish brown (10YR 5/8) and red (2.5YR 5/6) mottles common; gradual boundary.
IIB23tb (QU274)	225-295	Yellowish red (5YR 5/6) clay; moderate medium subangular to angular blocky structure; a few weak clay skins present; fairly dry, friable; many distinct fine and medium brownish yellow (10YR 6/8) and red (2.5YR 5/6) mottles common; gradual wavy boundary.

Horizon and Sample No.	Depth (cm.)	Description
IIB24b (QU275)	295-378	Strong brown (7.5YR 5/6) clay; strong medium subangular to angular blocky structure; fairly moist, friable; many distinct fine, medium, and coarse yellowish brown (10YR 5/8) and red (2.5YR 5/6) mottles common; gradual wavy boundary.
IIC1b (QU276)	378-448	Strong brown (7.5YR 5/6) clay; strong medium angular blocky structure; moist, firm; many coarse prominent brownish yellow (10YR 6/8), red (2.5YR 4/8, 7.5YR 5/8, and 10YR 4/8), and light gray (10YR 7/2) mottles common; gradual wavy boundary.
IIC2b (QU277)	448-598	Highly mottled clay which contains many decomposing rock fragments; strong medium subangular blocky structure; moist, friable to firm; many prominent coarse yellow (10YR 8/8), brownish yellow (10YR 6/8), pale brown (10YR 6/3), yellowish red (5YR 5/8), red (2.5YR 4/8), light gray to gray (10YR 6/1), and dark reddish gray (5YR 4/2) mottles common; gradual smooth boundary.
IIC3b (QU278)	598-868+	Highly mottled clay which contains many decomposing rock fragments; some of the latter look fresh but are soft and display the original crystal structure; strong medium subangular blocky structure, moist, friable to firm; mottles are similar as in the horizon above, but additional pinkish white (7.5YR 8/2) mottles are present; red mottles are more prominent than in the horizon above and there is an increase in the abundance of all mottles with depth.

Soils on Tilted Fault-Block Ridge II in the Piedmont Province

Soil Profile 7

Location: La Loma

The site is located on the backslope of tilted fault-block ridge II at its eastern end. It is in a cut on the west side of a footpath which leads from the La Marina alluvial/laharic fan to the village of La Loma.

Map Reference: Aguas Zarcas (1:50,000) 97856430

Elevation: 390 m Slope: 9-10° Aspect: Southeast

Drainage: Good Vegetation: Pasture

Parent Material: Pyroclastic deposits

Horizon and Sample No.	Depth (cm.)	Description
A1 (QU52)	0-18	Dark brown (10YR 3/3) sandy loam; well developed very fine to fine subangular blocky structure; fairly moist, friable; roots very abundant; clear smooth boundary.
A3t (QU53)	18-38	Dark yellowish brown (10YR 3/4) clay; weakly developed very fine to fine subangular blocky structure; weakly developed clay skins present; fairly moist, friable; roots abundant; clear smooth boundary.
B21t (QU54)	38-78	Dark yellowish brown (10YR 3/4) clay; well developed medium subangular blocky structure; weakly developed clay skins present; fairly moist, friable; some roots present; clear smooth boundary.
IIB22t (QU55)	78-98	Reddish brown (5YR 4/3) clay; well developed fine to medium subangular blocky structure; numerous weakly developed clay skins present; fairly moist, fairly friable; a few roots present; a few small rock fragments present; clear smooth boundary.
IIB23t (QU56)	98-108+	Reddish brown (5YR 4/4) clay; well developed fine to medium subangular blocky structure; a few weakly developed clay skins present; moist, friable; no roots present.

Soil Profile 11

Location: 2.4 km northwest of La Palmera

The site is located near the top of the outlier which rises to the north of the east central portion of tilted fault-block ridge II. It is in a cut on the north side of the road which connects the villages of La Palmera and San Francisco. Vertical cracking can be observed throughout the entire soil profile. However, it is most pronounced at the surface and in the upper two horizons of the soil.

Map Reference: Aguas Zarcas (1:50,000) 929683

Elevation: 250 m Slope: 3-4° Aspect: Southwest

Drainage: Good Vegetation: Coffee

Parent Material: Pyroclastic deposits

Horizon and Sample No.	Depth (cm.)	Description
Ap (QU77)	0-15	Dark reddish brown (5YR 3/4) clay loam; well developed very fine to fine angular blocky structure; well developed clay skins present; moist, fairly firm; roots very abundant; many earthworms present; material of this horizon which has collected in abandoned large root channels extends downward below this horizon; clear interrupted boundary.
B21t (QU78)	15-30	Dark reddish brown (5YR 3/4) clay; well developed fine angular blocky structure; many well developed clay skins present; moist, fairly firm; a few roots present; clear smooth boundary.
B22t (QU79)	30-58	Reddish brown (5YR 4/4) clay; well developed very fine to fine subangular blocky structure; a few weakly developed clay skins present; moist, fairly friable; a few roots present; gradual smooth boundary.
B23t (QU80)	58-88	Yellowish red (5YR 4/6) clay; well developed fine angular blocky structure; some well developed clay skins present; moist, fairly friable; a few roots present; gradual smooth boundary.
B24t (QU81)	88-120+	Yellowish red (5YR 4/6) clay; well developed fine angular blocky structure; many well developed clay skins present; moist, fairly friable; a few roots present.

Soil Profile 12

Location: 0.8 km northwest of La Palmera

The site is located in the middle part of the front scarp of tilted fault-block ridge II in its east central portion. It is in a cut on the west side of the road which connects the villages of La Palmera and San Francisco. Two distinct depositional units and associated soils are recognized at the site. They are separated by a stone line containing big boulders.

Map Reference: Aguas Zarcas (1:50,000) 94056735

Elevation: 260 m Slope: 14° Aspect: East

Drainage: Good Vegetation: Coffee

Parent Material: Laharic deposits underlain by pyroclastic deposits

Horizon and Sample No.	Depth (cm.)	Description
A1 (QU82)	0-8	Brown (7.5YR 4/4) clay; well developed crumb (very fine subangular blocky) structure; fairly dry, friable; roots very abundant; many earthworms and earthworm casts present; big boulders present on the surface; clear smooth boundary.
B21 (QU83)	8-30	Reddish brown (5YR 4/4) clay; well developed very fine subangular blocky structure; fairly moist, friable; roots present; gradual smooth boundary.
B22t (QU84)	30-73	Reddish brown (5YR 4/4) clay; well developed fine angular blocky structure; many well developed clay skins present; fairly moist, fairly friable; roots present; many small decomposing rock fragments present; clear smooth boundary.
IIA3tb (QU85)	73-98	Reddish brown (2.5YR 4/4) clay; well developed very fine subangular blocky structure; many well developed clay skins present; fairly moist, friable; clear smooth boundary.
IIB1tb (QU86)	98-118	Reddish brown (2.5YR 4/4) clay; well developed fine angular blocky structure; many well developed clay skins present; moist, friable; clear smooth boundary.
IIB21tb (QU87)	118-135	Red (2.5YR 4/6) clay; well developed very fine to fine angular blocky structure; many well developed clay skins present; moist, friable; gradual smooth boundary.

Horizon and Sample No.	Depth (cm.)	Description
IIB22tb (QU88)	135-160	Red (2.5YR 4/6) clay; well developed very fine to fine angular blocky structure; many well developed clay skins present; moist, friable; gradual smooth boundary.
IIB23tb (QU89)	160-188+	Red (2.5YR 4/6) clay; well developed very fine to fine angular blocky structure; many well developed clay skins present; moist, friable.

Soil Profile 14

Location: 0.3 km north of La Palmera

The site is located near the top of the front scarp of tilted fault-block ridge II in its east central portion. It is in a cut on the east side of the road which connects the villages of La Palmera and San Francisco.

Map Reference: Aguas Zarcas (1:50,000) 943671

Elevation: 320 m Slope: 3-4° Aspect: West

Drainage: Good Vegetation: Coffee

Parent Material: Laharic deposits

A1 (QU99)	0-30	Dark brown (7.5YR 3/2) clay; well developed very fine subangular blocky structure; moist, friable; roots very abundant; macrofaunal casts and eggs present; clear smooth boundary.
B1t (QU100)	30-50	Dark brown to brown (7.5YR 4/4) clay; well developed very fine to fine angular blocky structure; a few weakly developed clay skins present; moist, friable; a few large tree roots present; clear smooth boundary.
B21t (QU101)	50-75	Dark brown to brown (7.5YR 4/4) clay; well developed fine angular blocky structure; a few weakly developed clay skins present; moist, fairly friable; a few tree roots present; gradual smooth boundary.
B22t (QU102)	75-98+	Dark brown to brown (7.5YR 4/4) clay; well developed fine angular blocky structure; a few weakly developed clay skins present; moist, fairly friable.

Soil Profile 17

Location: 1 km south of Quebrada Azul

The site is located on the upper front scarp of tilted fault-block ridge II in its western portion. It is in a cut on the west side of the road which leads from Florencia to Muelle San Carlos. The A horizon of this soil has been eroded. Pronounced vertical cracking throughout the entire soil profile is present.

Map Reference: Aguas Zarcas (1:50,000) 831632

Elevation: 175 m Slope: 2-3° Aspect: East

Drainage: Good Vegetation: Pasture

Parent Material: Pyroclastic deposits

Horizon and Sample No.	Depth (cm.)	Description
B21t (QU121)	0-40	Dark reddish brown (5YR 3/2) clay; well developed fine to medium angular blocky structure; along vertical cracks many well developed clay skins present; fairly dry, friable; roots present which penetrate downward to 2 m in vertical cracks; accumulation of top soil in vertical cracks; diffuse interrupted boundary.
B22t (QU122)	40-115	Dark reddish brown (5YR 3/4) clay; well developed medium angular blocky structure; well developed clay skins present along vertical cracks; fairly moist, friable; roots present in vertical cracks; top soil accumulation in vertical cracks; diffuse interrupted boundary.
B23 (QU123)	115-158	Reddish brown (5YR 4/4) clay; well developed medium angular blocky structure; fairly moist, friable; a few roots and some top soil in vertical cracks; gradual interrupted boundary.
B24 (QU124)	158-185+	Reddish brown to yellowish red (5YR 4/5) clay; well developed fine angular blocky structure; fairly moist, friable; a few roots present in vertical cracks.

Soil Profile 19

Location: 2 km northwest of Santa Clara

The site is located on the backslope of tilted fault-block ridge II in its extreme western portion. It is in a cut on the west side of the road which leads from Santa Clara to Jabillos.

Map Reference: Fortuna (1:50,000) 786616

Elevation: 150 m Slope: ? Aspect: East

Drainage: Good Vegetation: Under big tree on pasture

Parent Material: Pyroclastic deposits

Horizon and Sample No.	Depth (cm.)	Description
A1 (QU131)	0-10	Dark reddish brown (5YR 3/4) silty clay; weakly developed very fine subangular blocky structure; moist, fairly friable; many grass roots, earthworms, and earthworm casts present; abrupt smooth boundary.
B1t (QU132)	10-30	Dark red (2.5YR 3.5/6) clay (?); well developed very fine subangular to angular blocky structure; a few well developed clay skins present; moist, fairly friable; many fine tree roots present; clear smooth boundary.
B21t (QU133)	30-55	Dark red (2.5YR 3.5/6) clay; very well developed fine angular blocky structure; very many well developed clay skins present; moist, fairly firm; medium-sized tree roots present; clear smooth boundary.
B22t (QU134)	55-88	Red (2.5YR 4/6) clay; weakly developed fine subangular blocky structure; many weakly developed and a few well developed clay skins present; moist, fairly friable; large tree roots present; gradual smooth boundary.
B23 t (QU135)	88-120	Red (2.5YR 4/7) clay; weakly developed very fine to fine angular blocky structure; many weakly developed and a few well developed clay skins present; moist, fairly friable; a few roots present; gradual smooth boundary.

Horizon and Sample No.	Depth (cm.)	Description
IIA3tb (QU136)	120-148	Dark red (2.5YR 3/6) silt; well developed fine angular blocky structure; well developed clay skins present; moist, fairly friable; a few roots present; gradual smooth boundary.
IIB21tb (QU137)	148-158+	Dark red (2.5YR 3/6) clay; well developed medium angular blocky structure; many well developed clay skins present; moist, fairly friable.

Soil Profile 20

Location: Cedral Norte

The site is located on the backslope of tilted fault-block ridge II in its west central portion. It is in a cut on the west side of a small side road about 100 m south of the main general store of the village.

Map Reference: Aguas Zarcas (1:50,000) 88556275

Elevation: 450 m Slope: 2-3° Aspect: Southeast

Drainage: Good Vegetation: Pasture

Parent Material: Pyroclastic deposits

Ap (QU139)	0-13	Reddish brown (5YR 4/3) clay; well developed very fine angular blocky structure; well developed clay skins present; moist, friable; many grass roots present; earthworms and earthworm casts present; clear smooth boundary.
B1t (QU140)	13-43	Reddish brown (5YR 4/4) clay; well developed very fine subangular blocky structure; many weakly and a few well developed clay skins present; moist, friable; many roots present; animal casts present; a few decomposing rock fragments present; clear smooth boundary.
B21t (QU141)	43-58	Dark red to red (2.5YR 3.5/6) clay; well developed very fine to fine angular blocky structure; many well developed clay skins present; moist, friable; many roots present; clear smooth boundary.

Horizon and Sample No.	Depth (cm.)	Description
B22t (QU142)	58-80	Red (2.5YR 4/6) clay; well developed fine angular blocky structure; many well developed clay skins present; moist, fairly friable; a few roots present; gradual smooth boundary.
B23t (QU143)	80-113	Red (2.5YR 4/7) clay; well developed very fine to fine angular blocky structure; many very well developed clay skins present; moist, fairly firm; a few roots present; gradual smooth boundary.
B3t (QU144)	113-145+	Red (2.5YR 4/8) clay; well developed very fine to fine angular blocky structure; many very well developed clay skins present; moist, fairly friable; small decomposing rock fragments present.

Soil Profile 32

Location: 1.6 km south of San Juan de Platanar

The site is located on the lower portion of the front scarp of tilted fault-block ridge II in its west central portion. It is in a cut on the west side of the dirt road which descends from Cedral Norte to the Río Platanar.

Map Reference: Aguas Zarcas (1:50,000) 87406495

Elevation: 175 m Slope: 12° Aspect: East

Drainage: Good Vegetation: Pasture

Parent Material: Pyroclastic deposits

Horizon and Sample No.	Depth (cm.)	Description
A1 (QU255)	0-3	Dark reddish brown (5YR 3/4) clay loam; strong fine subangular blocky structure; dry, very firm (hard surface crust); very many roots present; abrupt smooth boundary.
A3 (QU256)	3-25	Dark reddish brown (5YR 3/3.5) clay; strong fine subangular blocky structure; moist, friable; roots common; macrofaunal eggs common; abrupt wavy boundary.
IIB21t (QU257)	25-48	Red (2.5YR 4/6) clay; strong fine subangular blocky structure; moderate clay skins common; moist, friable; a few roots present; gradual smooth boundary.
IIB22t (QU258)	48-83	Red (2.5YR 4/6) clay; strong fine subangular to angular blocky structure; moderate clay common; moist, friable; gradual smooth boundary.
IIB23t (QU259)	83-110	Red to reddish brown (2.5YR 4/5) clay; strong fine sunangular to angular blocky structure; weak clay skins common; moist, friable; gradual smooth boundary.
IIB24t (QU260)	110-133+	Red to reddish brown (2.5YR 4/5) clay; strong fine to medium angular blocky structure; many moderate clay skins present; moist, friable.

Soil Profile 33

Location: 1.6 km south of San Juan de Platanar

The site is located on the lower portion of the front scarp of tilted fault-block ridge II in its west central portion. It is in a cut on the west side of the dirt road which descends from Cedral Norte to the Río Platanar 20 m upslope from site 32.

Map Reference: Aguas Zarcas (1:50,000) 87356485

Elevation: 178.5 m Slope: 14° Aspect: East

Drainage: Good Vegetation: Pasture

Parent Material: Pyroclastic deposits

Horizon and Sample No.	Depth (cm.)	Description
A1 (QU261)	0-28	Dark yellowish brown (10YR 3/4) clay; moderate medium crumb (subangular blocky) structure; the upper 2.5 cm consist of a hard surface crust as in profile 32; moist, friable; many roots present; abrupt smooth boundary.
B21 (QU262)	28-45	Dark brown to brown (7.5YR 4/4) clay; moderate very fine subangular blocky structure; moist, very friable; roots common; clear smooth boundary.
B22 (QU263)	45-83	Dark brown to brown (7.5YR 4/4) clay; moderate fine subangular blocky structure; moist, very friable; a few roots present; gradual smooth boundary.
B23 (QU264)	83-110	Dark brown to brown (7.5YR 4/4) clay; moderate fine subangular blocky structure; moist, friable; a few roots present; gradual smooth boundary.
B24 (QU265)	110-148+	Dark brown to brown (7.5YR 4/4) clay; strong fine subangular blocky structure; moist, friable.

Soils on Tilted Fault-Block Ridge III in the Piedmont Province

Soil Profile 5

Location: Puente de Casa

The site is located on the front scarp of tilted fault-block ridge III in its western part. It is in a cut on the north side of the road which leads from Ciudad Quesda to Florencia about 2.6 km east of Florencia.

Map Reference: Aguas Zarcas (1:50,000) 863599

Elevation: 410 m   Slope: 7°   Aspect: South

Drainage: Good   Vegetation: Sugar cane (?)

Parent Material: Laharic deposits which are underlain by pyroclastic deposits

Horizon and Sample No.	Depth (cm.)	Description
Ap (QU29)	0-18	Dark reddish brown (5YR 3/3) clay; well developed very fine to fine angular blocky structure; a few clay skins present; fairly dry, fairly friable; roots present; clear smooth boundary.
B21t (QU30)	18-55	Dark reddish brown (5YR 3/4) clay; well developed medium angular blocky structure; clay skins present in greater abunbundance than in the horizon above; fairly moist, fairly friable; a few roots present; clear smooth boundary.
B22 (QU31)	55-90	Reddish brown (5YR 4/4) clay; well developed fine to medium subangular blocky structure; moist, friable; a few roots present; at the bottom of this horizon a large very angular boulder is present which is partially embedded in the materials of the horizon below and which is part of an intermittent stone line which can be traced throughout the section in which the soil profile is located; clear smooth boundary.
IIB23 (QU32)	90-115	Dark red (2.5YR 3/6) clay; well developed medium angular blocky structure; fairly moist, friable; gradual smooth boundary.
IIB3t (QU33)	115-133	Red (2.5YR 4/6) clay; weakly developed very fine subangular blocky structure; a few clay skins present; fairly moist, fairly friable; gradual smooth boundary.

Horizon and Sample No.	Depth (cm.)	Description
IIC (QU34)	133-200+	Red (10R 4/7) clay; weakly developed very fine to fine subangular blocky structure; fairly moist, fairly friable; a few decomposing rock fragments present.

At the site about 10 m of the weathered tuff which underlies the laharic surface deposit was exposed. Since there was not sufficient time to describe and sample the entire exposure in detail, a few bulk samples (QU35, QU36, and QU37) were obtained from its lower portion. Furthermore, two additional bulk samples (QU38 and QU39) were collected 20 m and 30 m, respectively, upslope from the sampling site. Sample QU38 consists of unweathered tuff thought to be the parent material of the weathered tuff at site 5. Sample QU39 represents slihtly weathered tuff.

Sample No.	Description
QU35	Red (10R 5/8) silty loam; weakly developed fine subangular blocky structure; moist, friable; many red (7.5YR 4/8) and very pale brown (10YR 8/3) mottles and manganese shot present.
QU36	Red (10R 4/8) clay; weakly developed fine subangular blocky structure; moist, fairly friable; many red (7.5YR 5/6) mottles present.
QU37	Yellowish brown (10YR 5/8) silty loam; weakly developed fine subangular blocky structure; moist, friable; many pink (7.5YR 7/4) mottles and manganese shot present.
QU38	Very dark gray (10YR 3.5/1) sandy loam; moist, friable.
QU39	Very pale brown (10YR 7/3) silty loam; weakly developed fine subangular blocky structure; moist, fairly friable; manganese shot present.

Soil Profile 23

Location: Cedral Sur

The site is located near the top of tilted fault-block ridge III in its western portion. It is in a cut on the south side of the road which leads to the village about 2.1 km northeast from the point where it branches off from the road which connects Ciudad Quesada and Florencia. Near the site very large angular boulders were observed which had been dug out during the construction of a field entrance road.

Map Reference: Aguas Zarcas (1:50,000) 88906185

Elevation: 535 m Slope: ? Aspect: North

Drainage: Good Vegetation: Sugar cane (?)

Parent Material: Laharic deposits which are possibly overlain by volcanic ash

Horizon and Sample No.	Depth (cm.)	Description
A1 (QU164)	0-13	Dark brown (7.5YR 3/2) sandy clay loam; well developed very fine subangular blocky structure; moist, friable; many roots present; clear smooth boundary.
B1t (QU165)	13-30	Dark brown (7.5YR 3/2) clay; well developed very fine subangular to angular blocky structure; many weakly and a few well developed clay skins present; moist, friable; many roots present; clear smooth boundary.
B21 (QU166)	30-68	Dark reddish brown (5YR 3/4) clay; weakly developed very fine subangular blocky structure; moist, friable; roots present; clear smooth boundary.
B22 (QU167)	68-105	Dark reddish brown (5YR 3/3.5) clay; well developed fine angular blocky structure; moist, friable; roots present; gradual smooth boundary.
B23 (QU168)	105-133	Dark brown to brown (7.5YR 4/4) clay; well developed fine angular blocky structure; moist, friable; a few roots present; gradual smooth boundary.
B3 (QU169)	133-163+	Dark brown to brown (7.5YR 4/4) clay; well developed fine subangular blocky structure; moist, friable; decomposing rock fragments present.

Soil Profile 24

Location: 5.2 km northwest of Ciudad Quesada

The site is located near the top of tilted fault-block ridge III in its western portion to the southwest of site 23. It is in a cut on the west side of the road which connects Ciudad Quesada and Florencia. Two distinctly different depositional units and associated soils are recognized at the site.

Map Reference: Aguas Zarcas (1:50,000) 87656050

Elevation: 540 m Slope: 7° Aspect: East

Drainage: Good Vegetation: Pasture

Parent Material: Laharic deposits underlain by pyroclastic deposits

Horizon and Sample No.	Depth (cm.)	Description
Ap (QU171	0-13	Dark brown (7.5YR 3/2) loam; well developed fine subangular blocky structure; a few well developed clay skins present; moist, fairly friable; many roots, earthworms, and earthworm casts present; clear smooth boundary.
B21t (QU172)	13-28	Dark yellowish brown (10YR 4/4) clay; well developed very fine subangular to angular blocky structure; many well developed clay skins present; moist, fairly friable; many roots present; clear smooth boundary.
B22 (QU173)	28-50	Dark brown (7.5YR 3.5/4) clay; weakly developed very fine subangular to angular blocky structure; moist, friable; a few roots present; clear smooth boundary.
B23 (QU174)	50-83	Dark brown to brown (7.5YR 4/4) clay; well developed fine subangular blocky structure; moist, friable; a few roots present; clear smooth boundary.
B24 (QU175)	83-115	Dark brown to brown (7.5YR 4/4) clay; weakly developed fine angular blocky structure; fairly moist, friable; a few roots present; clear smooth boundary.
IIA2b (QU176)	115-133	Dark brown to brown (7.5YR 4/4) clay; well developed fine angular blocky structure; fairly moist, friable; a few tree roots present; gradual smooth boundary.

Horizon and Sample No.	Depth (cm.)	Description
IIB21b (QU177)	133-208	Reddish brown (5YR 4/4) clay; well developed fine angular blocky structure; fairly moist, friable; diffuse smooth boundary.
IIB22tb (QU178)	208-318	Reddish brown to red (2.5YR 4/5) clay; well developed very fine angular blocky structure; many well developed clay skins present; fairly dry, fairly firm; diffuse smooth boundary.
IIB3tb (QU179)	318-403+	Reddish brown (5YR 4/3.5) clay; well developed very fine angular blocky structure; many well developed clay skins present; fairly dry, fairly firm; small decomposing rock fragments and boulders present.

Soil Profile 31

Location: 4 km northwest of Ciudad Quesada

The site is located on the backslope of tilted fault-block ridge III in its western portion. It is in a cut on the west side of the road which connects Ciudad Quesada and Florencia. At the site four depositional units and associated soils are present.

Map Reference: Aguas Zarcas (1:50,000) 885598

Elevation: 540 m Slope: 9° Aspect: East

Drainage: Good Vegetation: Pasture

Parent Material: Pyroclastic deposits underlain by andesitic lava (?)

Horizon and Sample No.	Depth (cm.)	Description
A1 (QU238)	0-35	Dark yellowish brown (10YR 3/4) clay loam; weak medium crumb structure; moist, very friable; very many roots present; earthworms common; abrupt wavy boundary.
B1 (QU239)	35-55	Dark yellowish brown (10YR 3/4) clay; moderate fine subangular blocky structure; moist, friable; many roots present; clear wavy boundary.
B21 (QU240)	55-80	Dark brown to brown (7.5YR 4/4) clay; strong fine subangular blocky structure; moist, friable; many roots present; clear wavy boundary.
B22 (QU241)	80-120	Dark brown to brown (7.5YR 4/4) clay; strong fine to medium subangular blocky structure; moist, friable; roots common; gradual wavy boundary.
B23t (QU242)	120-166	Dark brown to brown (7.5YR 4/4) clay; strong medium subangular blocky structure; a few faint clay skins present; moist, friable; gradual wavy boundary.
B3 (QU243)	166-203	Dark brown to brown (7.5YR 4/4) clay; moderate fine angular blocky structure; moist, friable; gradual wavy boundary.

Horizon and Sample No.	Depth (cm.)	Description
IIB21tb1 (QU244)	203-253	Dark brown to brown (7.5YR 4/4) clay; strong medium to coarse subangular blocky structure; a few weak clay skins present; moist, friable; a few faint medium yellow mottle present; gradual wavy boundary.
IIB22tb1 (QU245)	253-308	Dark brown to brown (7.5YR 4/4) clay; strong medium to coarse subangular blocky structure; a few weak clay skins present; moist, friable; a few faint fine red and yellow mottles present; clear wavy boundary.
IIB3cnb1 (QU246)	308-348	Dark brown to brown (7.5YR 4/4) clay; strong fine angular blocky structure; moist, friable; a few distinct medium yellowish red (5YR 5/8) and red (2.5YR 4/8) mottles present; faint very fine white (light gray) mottles and manganese shot common; clear wavy boundary.
IIIB1cnb2 (QU247)	348-368	Dark brown to brown (7.5YR 4/4) clay; strong medium angular blocky structure; moist, friable; fine distinct yellow (10YR 7/6), yellowish red (5YR 5/8), red (2.5YR 4/8), and very pale brown (10YR 7/4) mottles and manganese shot common; clear wavy bounday.
IIIB21tcnb2 (QU248)	368-433	Reddish brown (5YR 4/4) clay; compound strong medium to coarse prismatic and strong medium to coarse angular blocky structure; many strong clay skins present; slickensides common; moist, very firm; many prominent red (2.5YR 4/8) mottles and fine manganese shot common; clear wavy boundary.
IIIB22tcnb2 (QU249)	433-465	Yellowish red (5YR 4/6) clay; strong fine to medium angular blocky structure; a few moderate clay skins present; moist, firm; many prominent fine and medium red (2.5YR 4/8) and distinct very fine white mottles common; fine manganese shot present; gradual wavy boundary.
IIICcnb2 (QU250)	465-498	Brown (7.5YR 5/4) clay; compound strong medium prismatic and strong fine to medium angular blocky structure; moist, firm; many prominent fine yellow (10YR 7/8), red (7.5YR 4/8), and light gray (10YR 7/1) mottles present; fine manganese shot common; clear wavy boundary.

Horizon and Sample No.	Depth (cm.)	Description
IVB21tcnb3 (QU251)	498-558	Reddish brown (5YR 4/4) clay; strong medium angular blocky structure; many strong clay skins present; fairly dry, very firm; many prominent fine to medium brownish yellow (10YR 6/8), red (2.5YR 4/8), light brownish gray (10YR 6/2), and gray (5YR 5/1) mottles present; fine manganese shot common; clear wavy boundary.
IVB22tcnb3 (QU252)	558-688	Dark brown to brown (7.5YR 4/4) clay; strong medium angular blocky structure; a few moderate clay skins present; fairly dry, firm; faint coarse reddish yellow (7.5YR 6/8), reddish brown to yellowish red (5YR 5/8), yellowish red (5YR 4/8), red (2.5YR 4/8), and gray (7.5YR 6/0) mottles common; fine manganese shot common; a few decomposing rock fragments (up to 10 cm in size) present; abrupt wavy boundary.
IVB3tcnb3 (QU253)	688-863	Dark brown to brown (7.5YR 4/4) clay loam; strong medium angular blocky structure; many strong clay skins; moist, very firm; embedded in the matrix are numerous fairly large partially and highly decomposed boulders which exhibit a multitude of colors; mottling is very prominent; the mottles vary in size from fine to coarse; the dominant colors of the mottles are yellowish brown (10YR 5/8), red (2.5YR 5/8), and very dark gray (5Y 3/1); manganese shot is common; clear wavy boundary.
IVCtcnb3 (QU254)	863-1113+	Dark brown to brown (7.5YR 4/4) clay loam; very similar characteristics as in the horizon above; however, mottles are coarser and more abundant; they are superimposed upon a mosaic of fairly large predominantly red, yellow, or gray segments of the weathering zone which have been produced by weathering of blocky andesitic lava; manganese shot is common.

Soils on Alluvial/Laharic Fans in the Piedmont Province

Soil Profile 8

Location: 1.5 km north of the Hacienda La Marina

The site is located on the central portion of the La Marina alluvial/laharic fan just west of the easternmost tributary of the Río La Ceiba. It is in a cut on the south side of a small side road about 0.6 km east from the point where it branches off from the road which leads from the Hacienda La Marina to the village of La Palmera. Three depositional units can be recognized.

Map Reference: Aguas Zarcas (1:50,000) 955638

Elevation: 320 m   Slope: 3-4°   Aspect: North

Drainage: Good   Vegetation: Pasture

Parent Material: Alluvium

Horizon and Sample No.	Depth (cm.)	Description
A1 (QU57)	0-33	Dark yellowish brown (10YR 3.5/4) loam; weakly developed very fine to fine subangular blocky strucutre; fairly moist, fairly friable; roots very abundant; many small (up to 7.5 cm in diameter) angular to rounded pebbles of different lithology and in different stages of weathering present; gradual smooth boundary.
IIB21cn (QU58)	33-60	Dark yellowish brown (10YR 3/4) clay; well developed medium subangular blocky structure; fairly moist, fairly friable; roots abundant; small iron concretions present; very few pebbles present except at the lower boundary of the horizon where a stone line of small pebbles exists; clear smooth boundary.
IIIB22cn (QU59)	60-83	Dark yellowish brown (10YR 3/4) clay loam; weakly developed fine subangular blocky structure; fairly moist, fairly friable; roots present; iron concretion present; gradual smooth boundary.

Horizon and Sample No.	Depth (cm.)	Description
IIIC1 cn (QU60)	83-110	Dark brown (10YR 3.5/3) sandy loam; well developed medium subangular to angular blocky structure; fairly moist, fairly friable; a few roots and a few iron concretions present; gradual smooth boundary.
IIIC2 (QU61)	110-143	Dark brown to dark yellowish brown (10YR 3/3.5) loamy sand; well developed medium subangular to angular blocky structre; fairly moist, fairly friable; a few roots present; gradual smooth boundary.
IIIC3 (QU62)	143-163	Dark brown to brown (10YR 4/3) sandy loam; well developed fine subangular to angular blocky structure; a few weakly developed clay skins present; fairly moist, fairly friable; gradual smooth boundary.
IIIC4 (QU63)	163-175+	Dark yellowish brown (10YR 4/4) sand; well developed fine angular blocky structure; fairly moist, fairly friable.

Soil Profile 16

Location: 1.1 km northwest of the Hacienda La Marina

The site is located on the west central portion of the La Marina alluvial/laharic fan. It is in a cut on the south side of the road which leads to the hamlet of La Selva about 0.7 km west from the point where it branches off from the road which leads from the Hacienda La Marina to the village of La Palmera.

Map Reference: Aguas Zarcas (1:50,000) 946632

Elevation: 340 m Slope: 3-4° Aspect: North

Drainage: Good Vegetation: Pasture

Parent Material: Alluvium

A1 (QU115)	0-13	Dark brown (7.5YR 3/2) sandy loam; well developed very fine subangular blocky structure; fairly moist, friable; many roots and many earthworms present; gradual smooth boundary.
A2 (QU116)	13-25	Dark brown (7.5YR 3/2) sandy loam; well developed very fine subangular blocky structure; fairly moist, friable; many roots and many earthworms present; abrupt smooth boundary.

Horizon and Sample No.	Depth (cm.)	Description
B1 (QU117)	25-40	Dark yellowish brown (10YR 3/4) loam; well developed very fine subangular blocky structure; fairly moist, friable; a few roots present; gradual smooth boundary.
B21 (QU118)	40-60	Dark yellowish brown (10YR 3/4) sandy clay loam; well developed very fine subangular blocky structure; fairly moist, friable; a few roots present; gradual smooth boundary.
B22 (QU119)	60-93	Dark yellowish brown (10YR 3/4) clay loam; well developed very fine subangular blocky structure; fairly moist, friable; a few roots present; diffuse smooth boundary.
B23 (QU120)	93-108+	Dark yellowish brown (10YR 3/4) clay; well developed very fine subangular blocky structure; fairly moist, friable; a few roots present.

<u>Soil Profile 4</u>

Location: 5.1 km southwest of the Hacienda La Marina

The site is located on the upper central portion of the Tessalia alluvial/laharic fan near the base of a recent andesitic lava flow. It is in a cut on the south side of the road which connects Ciudad Quesada with the Hacienda La Marina. At the site two depositional units appear to be present. However, no abrupt boundary exists between them. The surface soil has formed in both of these units.

Map Reference: Aguas Zarcas (1:50,000) 92655915

Elevation: 610 m Slope: 3° Aspect: North

Drainage: Good Vegetation: Pasture

Parent Material: Alluvium which is underlain by laharic deposits (?)

Horizon and Sample No.	Depth (cm.)	Description
A1 (23)	0-20	Dark yellowish brown (10YR 3/4) sandy loam; well developed very fine crumb structure; fairly moist, friable; roots abundant; clear smooth boundary.
B1 (QU24)	20-45	Dark brown to brown (7.5YR 4/4) clay; well developed very fine subangular blocky structure; fairly moist, friable; roots abundant; clear smooth boundary.
B21 (QU25)	45-80	Dark brown to brown (7.5YR 4/4) clay; well developed fine subangular blocky structure; fairly moist, friable; a few roots present, especially in vertical cracks; gradual smooth boundary.
B22 (QU26)	80-123	Dark brown to brown (7.5YR 4/4) clay; well developed medium subangular blocky structure; fairly moist, fairly friable; a few roots present, especially in vertical cracks; diffuse smooth boundary.
IIB23 (QU27)	123-163	Dark brown to brown (7.5YR 4/4) clay; well developed fine angular blocky structure; fairly moist, fairly friable; a few roots present, especially in vertical cracks; a few decomposing rock fragments present; diffuse smooth boundary.
IIC (QU28)	163-203+	Reddish brown (5YR 4/4) clay loam; well developed medium angular blocky structure; fairly moist, fairly friable; pieces of highly decomposed rock present.

Soil Profile 30

Location: 1.1 km northwest of the Centro Rural Metodista at Tessalia

The site is located on the lower central portion of the Tessalia alluvial/laharic fan just east of the Quebrada Marín. It is in a cut on the north side of a field path which trails along the east side of a tributary of the Quebrada Marín. The stratigraphy of the deposits is similar to that at site 4 except that the surface unit is thinner. The surface soil has formed in both depositional units.

Map Reference: Aguas Zarcas (1:50,000) 908607

Elevation: 440 m　　Slope: 14°　　Aspect: South

Drainage: Good　　Vegetation: Sugar cane and brush at the edge of the field

Parent Material: Alluvium which is underlain by laharic deposits

Horizon and Sample No.	Depth (cm.)	Description
A1 (QU232)	0-18	Dark brown to brown (7.5YR 4/4) clay loam; strong fine subangular blocky structure; moist, friable; many roots and many earthworms, earthworm casts, and macrofaunal eggs present; gradual smooth boundary.
B1 (QU233)	18-45	Dark yellowish brown (10YR 3/4) clay; moderate fine subangular blocky structure; moist, very friable; many roots present; earthworms and macrofaunal casts and eggs common; gradual smooth boundary.
B21 (QU234)	45-73	Dark yellowish brown (10YR 3/4) clay; strong medium subangular blocky structure; moist, friable; roots common; a few earthworms and macrofaunal casts and eggs present; gradual smooth boundary.
B22 (QU235)	73-93	Dark yellowish brown (10YR 3/4) clay; moderate fine subangular blocky structure; moist, friable; a few roots and a few earthworms present; a few faint fine red and yellow mottles present; clear smooth boundary.
IIB23cn (QU236)	93-125	Reddish brown (5YR 4/4) clay; strong fine to medium subangular blocky structure; moist, friable; a few roots and a few earthworms present; a few distinct medium and coarse red and yellow mottles and manganese shot present; gradual smooth boundary.
IIB3cn (QU237)	125-180+	Yellowish red (5YR 4/6) clay; strong fine to medium subangular blocky structure; moist, friable; distinct medium strong brown (7.5YR 5/7), yellowish brown (10YR 5/4), and red (10R 4/8) mottles and manganese shot common; pieces of decomposing rock with long-axes up to 10 cm in length present.

Soil Profile 22

Location: 3.1 km north-northwest of Ciudad Quesada

The site is located on the lower western portion of the Quesada alluvial/laharic fan near its boundary with the base of the backslope of tilted fault-block ridge III. It is in a cut on the south side of a small side road which branches off from the west side of the road that connects Ciudad Quesada with Florencia. Two depositional units are recognized in which the surface soil has formed.

Map Reference: Aguas Zarcas (1:50,000) 88655915

Elevation: 530 m Slope: 2° Aspect: North

Drainage: Good Vegetation: Pasture

Parent Material: Alluvium

Horizon and Sample No.	Depth (cm.)	Description
A1 (QU160)	0-8	Dark brown (7.5YR 3/2) loam; well developed very fine subangular blocky structure; moist, friable; many grass roots present; some small pebbles present; abrupt smooth boundary.
A3t (QU161)	8-28	Dark brown (7.5YR 3/2) sandy loam; well developed fine angular blocky structure; many well developed clay skins present; moist, firm; roots present; small pebbles present which are concentrated at the bottom of the horizon where they form a stone line; abrupt smooth boundary.
IIB1 (QU162)	28-60	Dark yellowish brown (10YR 3/4) loam; well developed fine subangular blocky structure; moist, friable; a few roots present; gradual smooth boundary.
IIB2 (QU163)	60-105+	Dark yellowish brown (10YR 3/4) clay loam; weakly developed fine subangular blocky structure; moist, friable; a few roots present.

Soils on Cinder Cones and Associated Pyroclastic Deposits in the Piedmont Province

Soil Profile 15

Location: Cerro Los Chiles

The site is located on the upper southeast slope of the northernmost of the cinder cones which rise above the lower portion of the Aguas Zarcas alluvial/laharic fan. It is in a cut on the north side of a footpath which ascends and leads to the summit of the cone.

Map Reference: Aguas Zarcas (1:50,000) 99157005

Elevation: 205 m Slope: 5° Aspect: South

Drainage : Good Vegetation: Tropical moist forest

Parent Material: Pyroclastic deposits

Horizon and Sample No.	Depth (cm.)	Description
A1 (QU105)	0-20	Dark reddish brown (2.5YR 3/4) clay; well developed very fine subangular blocky to crumb structure; very moist, friable; roots very abundant; many leaves and small branches of trees on top of the horizon; abrupt smooth boundary.
IIB1t (QU106)	20-48	Dark red (2.5YR 3/6) sandy clay; well developed very fine to fine angular blocky structure; many well developed clay skins present; moist, friable; roots common; diffuse smooth boundary.
IIIB21t (QU107)	48-75	Dark red (2.5YR 3/6) clay; well developed fine angular blocky structure; many well developed clay skins present; moist, friable; a few fine and a few big tree roots present; diffuse smooth boundary.
IIIB22t (QU108)	75-118	Dark red (2.5YR 3/6) clay; well developed fine to medium angular blocky structure; very many very well developed clay skins present; moist, friable; a few fine and a few big tree roots present; diffuse smooth boundary.

Horizon and Sample No.	Depth (cm.)	Description
IIIB23t (QU109)	118-135+	Dark red (2.5YR 3/7) clay; well developed fine to medium angular blocky structure; very many very well developed clay skins present; moist, friable; a few big tree roots present.

Soil Profile 3

Location: 1.2 km southwest of Buenos Aires

The site is located at the entrance to the village of Las Brisas in a cut on the east side of the road which leads to the village of La Unión. Two depositional units and associated soils are recognized. The surface deposit consists of recent volcanic ash which mantles the terrain between Buenos Aires and Venecia. The underlying deposit is composed of older pyroclastic materials.

Map Reference: Aguas Zarcas (1:50,000) 025614

Elevation: 440 m Slope: 5° Aspect: Northwest

Drainage: Good Vegetation: Coffee and orange trees

Parent Material: Pyroclastic deposits

A1 (QU18)	0-25	Dark yellowish brown (10YR 3/4) sandy loam; well developed very fine subangular blocky to crumb structure; moist, friable; roots very abundant; clear smooth boundary.
B2 (QU19)	25-40	Dark yellowish brown (10YR 3/4) sandy loam; well developed fine subangular blocky structure; moist, friable; roots present; clear smooth boundary.
C (QU20)	40-58	Dark yellowish brown (10YR 3/4) sandy loam; single grain structureless very ashy layer which contains cinders with long-axes up to 5 cm in length; the color of the cinders is dark gray to dark grayish brown (10YR 4/1.5); fairly moist, friable; abrupt smooth boundary.
IIB21b (QU21)	58-120	Dark yellowish brown (10YR 3/4) clay; well developed very fine to fine subangular blocky structure; moist, friable; roots present; clear smooth boundary.

Horizon and Sample No.	Depth (cm.)	Description
IIB22tb (QU22)	120148+	Dark brown to Brown (7.5YR 4/4) clay; well developed fine to medium subangular blocky structure; a few weak clay skins present; moist, fairly friable; a few roots present.

Soil Profile 6

Location: La Josefina

The site is located in the first cut east of the bridge which crosses the Río Tres Amigos on the south side of the road which leads to Pital. Four depositional units can be recognized. The upper three consist of pyroclastic materials the fourth is comprised of very coarse gravelly alluvium. Below the surface soil, one buried soil is present.

Map Reference: Aguas Zarcas (1:50,000) 03456850

Elevation: 160 m Slope: 2° Aspect: North

Drainage: Good Vegetation: Pasture with some trees near the river bluff

Parent Material: Pyroclastic deposits which are underlain by coarse gravelly alluvium

Ap (QU40)	0-35	Dark brown (7.5YR 3/2) clay; well developed fine to medium subangular blocky structure; fairly moist, fairly friable; roots present along tongues of softer materials in vertical cracks; diffuse wavy boundary.
B21t (QU41)	35-73	Dark brown to brown (7.5YR 4/4) clay; compound strong prismatic and weak fine subangular to angular blocky structure; a few clay skins present; fairly moist, fairly firm; a few roots present; gradual smooth boundary.
B22t (QU42)	73-110	Dark yellowish brown (10YR 3/4) clay; well developed medium angular blocky structure; clay skins common; fairly moist, fairly firm; gradual smooth boundary.
B3 (QU43)	110-145	Dark reddish brown (5YR 3/3) clay; well developed medium angular blocky structure; fairly moist, fairly firm; decomposing rock fragments present; clear smooth boundary.

Horizon and Sample No.	Depth (cm.)	Description
C1 (QU44)	145-178	Strong brown (7.5YR 3/4) clay loam; compound strong prismatic and weak fine subangular blocky structure; fairly moist, fairly friable; decomposing rock fragments present; gradual smooth boundary.
IIC2 (QU45)	178-213	Dark reddish brown (5YR 3/4) clay loam; well developed medium subangular blocky structure; fairly dry, fairly friable; decomposing rock fragments present; gradual smooth boundary.
IIC3 (QU46)	213-235	Yellowish red (5YR 4/6) clay loam; well developed fine angular blocky structure; fairly dry, fairly firm; larger pieces of decomposing rock present than in horizon above; gradual smooth boundary.
IIC4 (QU47)	235-325+	Red (2.5YR 5/6) clay loam; compound strong prismatic and weak fine angular blocky structure; fairly moist, fairly friable.
IIIA1cnb (QU48)	390-418	Brown (7.5YR 5/4) clay loam; well developed fine subangular blocky structure; fairly dry, fairly friable; red pieces of decomposing rock and manganese concretions present; clear smooth boundary.
IIIB21b (QU49)	418-453	Yellowish red (5YR 4/6) clay; compound strong medium prismatic and strong fine subangular blocky structure; fairly dry, fairly firm; small pieces of decomposing rock present; gradual smooth boundary.
IIIB22b (QU50)	453-470	Reddish brown (5YR 4/4) clay; compound strong prismatic and strong medium subangular blocky structure; fairly moist, fairly firm; many red and a few very small dark gray mottles present; gradual smooth boundary.
IIICb (QU51)	470-493+	Reddish brown (5YR 5/4) clay loam; compound strong prismatic and weak fine to very fine subangular blocky structure; moist, fairly firm; red and gray mottles present; clear smooth boundary with very coarse gravelly alluvium which extends downward to present channel of the Río Tres Amigos; boulders in the alluvium show spheroidal weathering.

Soil Profile 26

Location: 1 km northeast of La Josefina

The site is located approximately one kilometer to the northeast of of the bridge which crosses the Río Tres Amigos on the east side of the road which leads to Pital. Two massive depositional units which both appear to consists of pyroclastic materials are recognized. In the upper unit a well developed soil is present whereas in the second unit no indications of soil development were detected.

Map Reference: Aguas Zarcas (1:50,000) 04356865

Elevation: 170 m   Slope: 2°   Aspect: Northwest

Drainage: Good   Vegetation: Pasture with some trees at the top of the roadcut

Parent Material: Pyroclastic materials

Horizon and Sample No.	Depth (cm.)	Description
A11 (QU190)	0-15	Dark brown (7.5YR 3/2) clay loam; moderate medium crumb structure; fairly dry, friable; many roots present; macrofaunal casts and eggs present; clear smooth boundary.
A12 (QU191)	15-30	Dark brown (7.5YR 3/2) clay loam; moderate fine to medium subangular blocky structure; fairly moist, friable; a few roots present; clear smooth boundary.
B1 (QU192)	30-48	Dark yellowish brown (10YR 3/4) clay; moderate medium subangular blocky structure; fairly moist, friable; a few roots present; gradual smooth boundary.
B21 (QU193)	48-88	Dark yellowish brown (10YR 3/4) clay; weak fine subangular blocky structure; fairly moist, very friable; a few roots present; clear smooth boundary.
B22 (QU194)	88-123	Dark yellowish brown (10YR 3/4) clay; moderate fine to medium subangular blocky structure; fairly moist, friable; a few roots present; clear smooth boundary.
B23 (QU195)	123-145	Dark yellowish brown (10YR 3.5/4) clay; strong medium subangular blocky structure; fairly moist, friable; clear smooth boundary.

Horizon and Sample No.	Depth (cm.)	Description
B24 (QU196)	145-180	Dark brown (7.5YR 3.5/4) clay; strong medium subangular to angular blocky structure; fairly moist, friable; clear smooth boundary.
B25 (QU197)	180-215	Dark yellowish brown (10YR 3/4) clay; compound very thick platy and very strong medium to coarse angular blocky structure; fairly moist, fairly firm; clear smooth boundary.
B26 (QU198)	215-240	Dark brown to dark yellowish brown (10YR 3/3.5) clay; compound very thick platy, strong medium prismatic, and strong fine and coarse angular blocky structure; weak clay skins present; fairly moist, firm; a few pieces of decomposing rock with long-axes up to 1 cm in length present; clear smooth boundary.
B3cn (QU199)	240-273	Dark yellowish brown (10YR 3/4) clay loam; strong medium subangular blocky structure; fairly moist, fairly friable; a few pieces of decomposing rock with long-axes up to 3 cm in length present; manganese shot present; clear smooth boundary.
C1 (QU200)	273-298	Layer of small rounded pebbles with long-axes up to 0.5 cm in length in a sandy loam matrix which shows weak cementation by iron oxides and manganese dioxide; abrupt slightly wavy boundary.
IIC2 (QU201)	298-323	Dark brown (7.5YR 3/2) silt loam; strong coarse subangular blocky structure; fairly moist, fairly friable; gradual smooth boundary.
IIC3 (QU202)	323-415	Dark brown (7.5YR 3.5/4) silt loam; moderate medium to coarse subangular blocky structure; fairly moist, fairly friable; distinct fine red and yellow mottles caused by decomposing rock fragments common; clear smooth boundary.
IIC4cn (QU203)	415-490	Dark reddish brown (5YR 3/3.5) silt loam; strong medium to coarse subangular blocky structure; fairly moist, fairly firm; distinct medium red and yellow mottles caused by decomposing rock fragments and manganese shot present; gradual smooth boundary.

Horizon and Sample No.	Depth (cm.)	Description
IIC5cn (QU204)	490-563	Weak red (2.5YR 4/2.5) silt loam; strong coarse subangular blocky structure; fairly moist, fairly firm; many distinct red and yellow mottles caused by decomposing rock fragments and manganese shot present; gradual smooth boundary.
IIC6cn (QU205)	563-613	Dark reddish brown (5YR 3/4) silt loam; compound strong coarse prismatic and moderate medium subangular blocky structure; fairly moist, fairly firm; many distinct medium red and yellow mottles caused by decomposing rock fragments and manganese shot present; clear smooth boundary.
IIC7 (QU206)	613-658	Weak red (2.5YR 4/2.5) silt loam; compound strong medium prismatic and strong medium subangular blocky structure; fairly moist, fairly firm; many prominent fine red and yellow mottles caused by decomposing rock fragments present; clear smooth boundary.
IIC8 (QU207)	658-703	Weak red (2.5YR 4/2) silt loam; compound strong medium prismatic and weak fine subangular blocky structure; moist, friable; very many prominent medium and coarse yellow, red 10R 4/8), and very dark gray (2.5YR 3/0) mottles caused by decomposing rock fragments present; abrupt smooth boundary.
IIC9cn (QU208)	703-725	Red (2.5YR 4/7) loam; strong medium subangular blocky structure; moist, fairly friable; extremely many prominent medium and coarse red, yellow, dark gray (5YR 4/1.5), and strong brown (7.5YR 5/8) mottles caused by decomposing rock fragments and manganese shot present; abrupt smooth boundary.
IIC10cn (QU209)	725-748+	Yellowish brown (10YR 5/5) loam; moderate medium subangular blocky structure; moist, fairly firm; many prominent fine, medium, and coarse red, yellow, dark reddish brown (5YR 3/2), and strong brown (7.5YR 5/6) mottles caused by decomposing rock fragments and manganese shot present.

APPENDIX II

PROCEDURES FOR LABORATORY ANALYSES

In general, standard procedures were followed in the laboratory analyses. Procedures for the various analyses are provided for reference. In addition, information is given about the kind and number of soil samples on which analyses were performed; some soil terms are defined; and several tests which were carried out preceding actual soil analysis are described.

Particle-Size Distribution

The particle-size distribution or the relative proportion of sand, silt, and clay was determined for all 278 disturbed soil samples collected at the 34 major sampling sites and for additional 160 disturbed soil samples obtained in exposures between major sampling sites. Particle-size analysis was carried out by the pipette method (Kilmer and Alexander, 1949, p. 15-24). All analyses were performed on 20.0 g (grams) of air-dried soil which had been passed through a 2 mm (millimeter) aperture sieve (ASTM No. 10).

Procedure

Pretreatment of the soil samples consisted of the removal of organic matter by hydrogen peroxide (H_2O_2). Each sieved and weighed sample was placed into a 250 ml (milliliter) conical flask and covered with 50 ml of distilled water and 15 ml of 30% H_2O_2. After the reaction had ceased, a few additional drops of H_2O_2 were added in order to determine whether or not the pretreatment had been complete. If further reaction was evident, additional H_2O_2 was added until no further reaction occurred. The advantage of this pretreatment is that it breaks down the humus-clay bonds, thus making dispersion of the soil easier.

Dispersion of soil samples was achieved by adding 10 ml of buffered sodium hexametaphosphate (Calgon) solution. After dispersion, soil samples were transferred to mixing cups and stirred for five minutes on a Hamilton Beach

Model 55 milk-shake type mixer. After stirring, they were washed with distilled water into insulated 1,000 ml measuring cylinders and were made up to volume with distilled water. Then, the temperature of the suspensions was measured and, with the aid of temperature-time curves (Day, 1965, p. 548), the exact times for obtaining the American silt and clay (0.05-0.002 mm) and the International silt and clay (0.02-0.002 mm) fractions were calculated.

Before starting the actual measurements, each suspension was thoroughly shaken end-over-end for one minute. Then, a 25 ml pipette was lowered so that its tip was just touching the surface of the suspension. Fifteen seconds before aliquots were due to be taken, the pipette was lowered slowly until it was immersed exactly 10 cm. At the calculated times, suction was applied smoothly to the pipette so as to fill it in about 30 seconds. From the pipette, 25 ml aliquots were transferred to weighed 100 ml beakers.

The clay fraction (<0.002 mm) of the soil samples was obtained between six and eight hours after settling had started. Before an aliquot was taken, the temperature of the suspension was measured and, with the aid of temperature-time-depth curves, the exact sampling depth was determined. Fifteen seconds before an aliquot was due to be taken, the pipette was lowered slowly to the appropriate depth. At the calculated time, suction was applied smoothly to the pipette so as to fill it in about 30 seconds. From the pipette, a 25 ml aliquot was transferred to a weighed 100 ml beaker.

All aliquots of each suspension were evaporated in a constant-temperature oven in order to obtain dry aliquots of a soil sample. After having been cooled in a dessicator containing anhydrous calcium chloride, the beakers containing the dry soil aliquots were weighed. The exact weight of each soil aliquot was obtained by subtracting the weight of the beaker plus a correction factor (0.0205 g), pertaining to the amount of buffered sodium hexametaphosphate salts contained in a 25 ml aliquot of the suspension, from the combined weight of the beaker and soil aliquot.

After having expressed the weight of each soil aliquot as a percentage of the total amount of soil contained in a 25 ml aliquot of the 1,000 ml suspension (0.5000 g), the percentages of the different size fractions of a soil sample could be determined. The percentage of clay was obtained directly from the experiment. The percentage of the American silt fraction was determined by subtracting the percentage of clay from the percentage of the American silt and clay fraction. Similarly, the percentage of the International silt fraction was obtained by subtracting the percentage of clay from the percentage of the International silt and clay fraction. The percentage of sand was calculated by subtracting the percentage of the American silt and clay fraction from 100 percent.

Free Iron-Oxide Content

The free iron-oxide content was determined for all 278 soil samples at the 34 major sampling sites. Free iron-oxide determinations were carried out by the sodium dithionate method (Olson, 1965, p. 971-972).

Before actual measurements were undertaken, the feasibility of using the entire soil in the free iron-oxide analyses was investigated. A randomly selected soil, which had a moderate clay content of 48 percent and contained 29 percent sand and 23 percent clay, was divided into different size fractions for each of which the percentage of free iron oxides was determined (Table 16). In addition, the operational error was investigated.

TABLE 16.--Percentages of Free Iron Oxides of Different Size Fractions of a Clay Soil

Size Fraction (mm)	Weight of Sample (g)	Free Fe_2O_3 (%) First Titration	Free Fe_2O_3 (%) Second Titration
2.0 - 1.0	5.0007	9.7	9.6
1.0 - 0.5	5.0002	9.1	9.1
0.5 - 0.25	5.0009	7.7	7.7
0.25 - 0.11	5.0001	8.4	8.4
0.11 - 0.05	4.9996	8.1	8.0
< 0.05	5.0000	8.4	8.4
Mean		8.6	8.5
Standard Deviation		0.656	0.612

Several conclusions can be drawn from the test: (1) When free iron-oxide determinations are carried out very carefully, the operational error is small. The largest difference in the free iron-oxide content of duplicate titrations is only 0.1 percent. (2) No definite relationship seems to exist between particle size and the percentage of free iron oxides. However, variations in the percentage of free iron oxides appear to be greater in the larger than in the smaller size fractions. (3) The standard deviation in the two titration sets is relatively high when all size fractions are included in the calculations, since differences between the highest and lowest percentages of free iron oxides amount to 2.0 and 1.9 percent, respectively. On the other hand, when only the fine sand and smaller size fractions are considered, differences between the highest and lowest percentages of free iron oxides are only 0.3 and 0.4 percent and standard deviations amount to only 0.014 and 0.019, respectively. In order to minimize possible errors resulting from particle-size variations, soil samples were crushed very finely with a porcelain pestle and mortar prior to weighing.

Procedure

Each sample, consisting of 5.0000 ± 0.0005 g of finely crushed air-dried soil, was placed into a 250 ml conical flask together with 5.0 g of sodium dithionate ($Na_2S_2O_4$) and 100 ml of distilled water. Then, the flask was corked with a rubber stopper and allowed to stand for 20 minutes before it was placed on a wrist-action shaker. After 16 hours of shaking, the sample was transferred to a 250 ml beaker and the pH of the suspension was adjusted to 3.5 to 4.0 with 1N hydrochloric acid (HCl). During the following hour the suspension was stirred five times with a glass rod. The sample was then transferred to a 250 ml volumetric flask, diluted to volume with distilled water, and shaken end-over-end 20 times before part of the suspension was poured into a 100 ml centrifuge tube. After centrifuging for 5 minutes at 750 rpm, the supernatant liquid was stored in a 250 ml conical flask. The process of shaking and centrifuging was repeated two more times in order to obtain the supernatant liquid of the entire sample.

The free iron-oxide determinations were conducted on 50 ml of the soil extract, representing 1.008 g of the soil. After 50 ml of the soil extract had been transferred from the storage flask to a 400 ml beaker, 50 ml of distilled water and 15 ml of 30% H_2O_2 were added, the beaker covered with a watch glass, and placed on an oscillating hot plate. After a reaction had started, the beaker was removed from the hot plate and the solution was allowed to stand until the reaction had practically ceased. The beaker was then placed again on the hot plate and the solution was boiled for 10 to 15 minutes. In order to test whether or not all ferrous iron had been transformed into ferric iron, three drops of the solution and two drops of 0.1% potassium ferricyanide $[K_3Fe(CN)_2]$ solution were placed on a spot plate. If ferrous iron was still present, the color turned to dark olive green or Prussian blue. In such a case, additional 5 ml of H_2O_2 were added and the sample was boiled again for 5 to 10 minutes. Then the test for ferrous iron was repeated. A yellow color indicated the absence of ferrous iron.

When all the ferrous iron had been converted to ferric iron, a slight excess of 7N ammonium hydroxide (NH_4OH) was added and the sample was boiled again on the hot plate for 15 to 20 minutes. After the ferric hydroxide [$Fe(OH)_3$] precipitate, which had formed when the ammonium hydroxide was added, had been dissolved with 15 ml of 6N hydrochloric acid (HCl), the solution was heated to 90°C on the hot plate and while stirring, stannous chloride ($SnCl_2$) reagent was added drop by drop until the yellow color of the solution changed to a clear color. Four drops of $SnCl_2$ reagent were added in excess and the sample was cooled in a cold-water bath to room temperature.

After the solution had cooled, 15 ml of saturated mercuric chloride ($HgCl_2$) solution were added rapidly. If the right amount of $SnCl_2$ reagent had been added, a light, silky precipitate formed, and the analysis was continued. The solution was then diluted to about 125 ml with distilled water and 5 ml of 85% orthophosphoric acid (H_3PO_4) and 10 drops of 0.16% barium diphenylamine sulfonate solution were added. The final titration was done with 0.1N potassium dichromate ($K_2Cr_2O_7$) solution to a violet-blue endpoint.

The quantity of free iron oxides is usually expressed as percentage of iron oxides in the soil and calculated as follows:

$$\% \; Fe_2O_3 = \text{ml of } K_2Cr_2O_7 \text{ used} \times \text{Normality of } K_2Cr_2O_7 \times 7.92.$$

Soil Reaction

The soil reaction was determined for all 438 disturbed soil samples collected in the study area. Determinations of soil pH were carried out on 1:2.5 soil-water suspension by glass electrode (Peech, 1965, p. 920-923), using a Fisher Model 210 Accumet pH meter.

Before the decision was made to perform pH measurements on the soil suspension, soil pH was also determined on the supernatant liquid of soil samples. The tests showed that duplicate readings on the supernatant liquid differed more widely and were slightly higher than those obtained on the soil suspension. Caspall (1970, p. 70), who performed a correlation and regression analysis on the results of both techniques, found a correlation coefficient of $r = 0.9346$.

Procedure

Samples, consisting of 20.0 g of air-dried soil which had been passed through a 2 mm aperture sieve (ASTM No. 10), were placed into 100 ml beakers and covered with 50 ml of distilled water. Then, samples were stirred thoroughly two times with a glass rod before being allowed to stand for at least 16 hours.

Just prior to making pH measurements, samples were stirred again. For each sample, at least two pH readings were obtained. If the first two readings differed, a third was made. If two of the three readings were identical, this value was accepted as the pH of the sample. If all three readings differed, the arithmetic mean of the three values was taken as the sample pH.

Bulk Density

Bulk density (mass or weight of a unit volume of dry soil including both soil solids and pore spaces) was determined for 122 undisturbed soil samples from 21 of the 34 major sampling sites. Determinations of bulk density were made by the core method (Blake, 1965, p. 375-377).

Procedure

In the field, undisturbed core samples of known volume were collected by (1) pressing a cylindrical metal container firmly but not forcefully into the face of the soil profile at a given soil horizon and by (2) removing the container and sample with the least possible disturbance in order to preserve the volume of the sample as it existed *in situ*.

In the laboratory, samples were transferred to 100 ml beakers of known weight and dried in a constant-temperature oven at temperatures between 100-110°C for at least eight hours. After having been cooled in a dessicator containing anhydrous calcium chloride, the beakers holding the oven-dry samples were weighed. The weight of each soil sample was determined by subtracting the weight of the beaker from the combined weight of the beaker and sample. The bulk density of the sample in g/cc (grams per cubic centimeter) was calculated by dividing the weight of the oven-dry sample by its known volume.

Moisture Content

The moisture content was determined for 97 of the 122 undisturbed soil samples for which bulk-density determinations were made. Moisture-content determinations could not be performed on all undisturbed soil samples because some samples had lost appreciable amounts of moisture as a result of puncture of plastic storage bags during shipment. Moreover, all percentage moisture determinations are believed to be slightly too low because some moisture had generally condensed on the inside of plastic storage bags and is not accounted for in the weight of wet soil samples. Moisture content was determined by gravimetry with oven drying (Gardner, 1965, p. 92-93).

Procedure

The gravimetric method employed involved (1) obtaining the weight of the wet soil sample, (2) drying the wet soil sample in a constant-temperature oven at temperatures between 100-110°C, and (3) obtaining the weight of the oven-dry sample. The weight of the wet soil sample was determined after transfer from the plastic storage bag to a 100 ml beaker of known weight. After weighing the beaker containing the wet soil sample, the weight of the beaker was subtracted from the combined weight of the beaker and wet soil sample. The weight of the oven-dry sample is identical to that obtained for bulk-density determinations (p. 240). The moisture content of each soil sample was determined by first subtracting the weight of the oven-dry soil sample from that of the wet soil sample. Then, the difference between the weights of the wet and oven-dry soil samples was divided by the weight of the oven-dry sample in order to obtain the ratio of the weight of water to that of the oven-dry soil. The percentage moisture content of each soil sample was calculated by multiplying this ratio by 100.

Aggregate Stability

Aggregate stability (stability of soil aggregates in water) was determined for only a very limited number of disturbed soil samples because it was soon found that this pedogenic property did not vary appreciably among the differing soils in the study area. Aggregate stability was determined by the index of structure (Sombroek, 1966, p. 122; Harris, 1971, p. 156).

Procedure

In order to determine the index of structure, both the percentages of total clay and natural clay in a soil sample have to be known. Total clay was determined after destruction of organic matter with hydrogen peroxide and dispersion of the soil sample with buffered sodium hexametaphosphate (Calgon) solution. Natural clay was determined after soaking the soil sample in distilled water for

16 hours. Both analyses were carried out on 20.00 g of air-dried soil which had been passed through a 2 mm aperture sieve (ASTM No. 10). Following the differing pretreatments, soil samples were stirred for five minutes on a Hamilton Beach Model 55 milk-shake type mixer, transferred to insulated 1,000 ml measuring cylinders, and made up to volume with distilled water. Both clay fractions were determined by the pipette method (p. 233-234). In calculating the weight of the natural clay fraction, subtraction of the correction factor pertaining to the amount of buffered sodium hexametaphosphate salts contained in a 25 ml aliquot of the suspension of the dispersed soil sample was omitted. The index of structure was calculated as follows:

$$\text{Index of Structure} = 100 \left(1 - \frac{\text{Natural Clay}}{\text{Total Clay}} \right).$$

APPENDIX III

RESULTS OF LABORATORY ANALYSES

Results of laboratory analyses performed on individual soil samples are tabulated according to soil profiles. As in Appendix I, soil profiles are presented by physiographic province and landform type. Data for soil profiles 25 and 27 are omitted because they were not used in the present study. The following abbreviations are used in the tables:

Particle-Size Analysis

AmS. = American Sand = 2.0-0.05 mm

AmSi. = American Silt = 0.05-0.002 mm

ISi. = International Silt = 0.02-0.002 mm

C. = Clay = <0.002 mm

Soil Texture

S = Sand
LS = Loamy Sand
SL = Sandy Loam
L = Loam
SiL = Silt Loam
Si = Silt
SCL = Sandy Clay Loam
SiCL = Silty Clay Loam
CL = Clay Loam
SC = Sandy Clay
SiC = Silty Clay
C = Clay

TABLE 17.--Soils on Small Hills of Laharic Origin in the Atlantic Lowland Province

Profile No.	Sample No.	Horizon	Depth (cm.)	Particle-Size Analysis (%) AmS.	AmSi.	C.	ISi.	Texture	ISi./C. Ratio	pH 1:2.5 H_2O	Free Fe_2O_3 (%)	Bulk Density (g./cc.)	Moisture Content (%)	Index of Structure
2	QU 13	A1	0-15	38	26	36	22	CL	0.61	5.2	7.7	0.82	40	75
	QU 14	B1	15-35	16	13	71	11	C	0.15	5.6	8.5	0.84	..	98
	QU 15	B21	35-60	15	5	80	4	C	0.05	5.5	8.9	0.81	..	99.5
	QU 16	B22t	60-98	13	6	81	5	C	0.06	5.1	8.4	0.83	40	99.6
	QU 17	B23t	98-125+	11	9	80	5	C	0.06	4.9	8.4	0.92	40	99.4
10	QU 71	Ap	0-13	50	20	30	17	SCL	0.57	5.1	7.6	0.72	..	..
	QU 72	B1t	13-28	27	19	54	17	C	0.31	5.1	8.8	0.75	33	..
	QU 73	B21t	28-50	20	10	70	9	C	0.13	5.1	8.3	0.76	..	..
	QU 74	B22t	50-68	22	5	73	4	C	0.05	4.8	7.9	0.78	..	..
	QU 75	B23t	68-80+	24	4	72	3	C	0.04	4.9	7.9	0.82	39	..
21	QU145	A1	0-13	37	29	34	23	CL	0.68	5.3	8.3	..	..	..
	QU146	B21t	13-25	26	21	53	20	C	0.38	5.4	8.3	..	..	..
	QU147	B22	25-55	16	13	71	11	C	0.15	5.1	9.6	..	..	..
	QU148	B23	55-75	19	13	68	11	C	0.16	5.1	8.2	..	..	..
	QU149	IIA1b	75-90	23	12	65	10	C	0.15	5.2	7.1	..	..	..
	QU150	IIB21tb	90-100	6	12	82	10	C	0.12	5.3	8.6	..	..	..
	QU151	IIB22tb	100-155	20	8	72	5	C	0.07	5.0	8.0	..	..	..
	QU152	IIB23tb	155-203	21	6	73	5	C	0.07	4.8	8.5	..	..	..
	QU153	IIB24tb	203-263	21	12	67	11	C	0.16	4.9	9.7	..	..	..
	QU154	IIB25tb	263-338+	23	16	61	14	C	0.23	4.9	9.4	..	..	..

TABLE 17.--Continued

Profile No.	Sample No.	Horizon	Depth (cm.)	Particle-Size Analysis (%) AmS.	AmSi.	C.	ISi.	Texture	ISi./C. Ratio	pH 1:2.5 H_2O	Free Fe_2O_3 (%)	Bulk Density (g./cc.)	Moisture Content (%)	Index of Structure
28	QU220	Ap	0-23	17	16	67	13	C	0.19	5.6	7.0	..	..	..
	QU221	B21	23-43	14	9	77	9	C	0.12	5.7	8.2	..	..	..
	QU222	B22t	43-68	13	7	80	4	C	0.05	5.15	8.5	..	..	..
	QU223	B23t	68-120+	13	7	80	5	C	0.06	5.0	8.6	..	..	..
29	QU224	A1	0-38	16	15	69	13	C	0.19	4.65	8.2	..	..	..
	QU225	B21	38-70	11	7	82	5	C	0.06	4.65	8.7	..	..	..
	QU226	B22t	70-108	13	2	85	2	C	0.02	4.9	9.7	..	..	..
	QU227	B23t	108-148	11	6	83	5	C	0.06	5.05	9.1	..	..	..
	QU228	B24t	148-158	8	7	85	7	C	0.08	4.95	8.7	..	..	..
	QU229	B25t	158-220	13	7	80	6	C	0.08	4.9	9.4	..	..	..
	QU230	IIB26t	220-255	26	9	65	8	C	0.12	4.85	10.6	..	..	..
	QU231	IIB27t	255-380	20	12	68	9	C	0.13	4.65	11.7	..	..	..

TABLE 18.--Soils on Alluvial Plains in the Atlantic Lowland Province

Profile No.	Sample	Horizon	Depth (cm.)	Particle-Size Analysis (%)				Texture	ISi./C. Ratio	pH 1:2.5 H_2O	Free Fe_2O_3	Bulk Density (g./cc.)	Moisture Content (%)	Index of Structure
				AmS.	AmSi.	C.	ISi.							
1	QU 1	A1	0-8	54	27	19	17	SL	0.89	5.2	5.9	..	..	..
	QU 2	B1	8-13	54	28	18	17	SL	0.94	5.6	6.0	..	..	..
	QU 3	B21	13-48	56	25	19	15	SL	0.79	5.2	5.9	..	..	..
	QU 4	IIB22	48-63	57	29	14	19	SL	1.36	5.1	5.7	..	..	..
	QU 5	IIC	63-75	53	35	12	19	SL	1.58	4.7	4.6	..	..	..
	QU 6	IIIA1b	75-88	48	32	20	17	L	0.85	5.1	5.9	..	..	..
	QU 7	IIIB2b	88-103	25	53	22	18	SiL	0.82	5.1	6.6	..	..	..
	QU 8	IIIB3b	103-123	50	36	14	18	L	1.29	5.7	5.1	..	..	..
	QU 9	IIIC1b	123-138	72	21	7	12	SL	1.71	5.6	4.0	..	..	..
	QU 10	IVC2cnb	138-148	81	17	2	8	LS	4.00	5.4	3.2	..	..	..
	QU 11	VCb	148-158	68	24	8	12	SL	1.50	5.3	3.3	..	..	..
	QU 12	VIC4b	158-203+	96	3	1	2	S	2.00	5.7	3.1	..	..	..

TABLE 19.--Soils on Tilted Fault-Block Ridge I in the Piedmont Province

Profile No.	Sample No.	Horizon	Depth (cm.)	Particle-Size Analysis (%) AmS.	AmSi.	C.	ISi.	Texture	ISi./C. Ratio	pH 1:2.5 H_2O	Free Fe_2O_3 (%)	Bulk Density (g./cc.)	Moisture Content (%)	Index of Structure
9	QU 64	Ap	0-13	21	34	45	27	C	0.60	4.8	8.7	0.85	37	..
	QU 65	B21t	13-28	13	19	68	17	C	0.25	5.0	8.4	0.87	38	..
	QU 66	B22t	28-43	19	16	65	14	C	0.22	5.1	8.7	0.95	38	..
	QU 67	B23	43-78	15	9	76	9	C	0.12	5.0	9.5	0.93	39	..
	QU 68	B24	78-105+	16	10	74	9	C	0.12	5.2	8.4	0.91	46	..
13	QU 90	A1	0-15	50	30	20	17	L	0.85	6.2	7.2	0.67	..	..
	QU 96	B21t	15-33	32	17	51	13	C	0.25	5.9	7.8	0.78	39	..
	QU 97	B22t	33-50	25	17	58	16	C	0.28	5.7	7.4	0.76	38	..
	QU 92	IIB23	50-85	25	22	53	16	C	0.30	5.6	7.8	0.78	..	..
	QU 93	IIB24	85-130	33	16	51	12	C	0.24	5.7	7.9	0.93	37	..
	QU 94	IIB25t	130-167	37	10	53	8	C	0.15	5.2	7.2	0.79	42	..
	QU 95	IIB3t	167-185+	34	19	47	14	C	0.30	4.9	7.8	0.80	..	..
18	QU125	Ap	0-43	37	28	35	22	CL	0.63	5.0	7.8	0.74	45	..
	QU126	B21t	43-65	17	14	69	12	C	0.17	4.9	8.0	0.74	..	..
	QU127	B22tcn	65-90	21	12	67	11	C	0.16	5.0	8.3	0.93	46	..
	QU128	B23tcn	90-133	20	14	66	13	C	0.20	4.9	5.9	0.78	44	..
	QU129	B23t	133-160+	22	5	73	4	C	0.05	4.7	8.6	0.75	47	..

TABLE 19.--Continued

Profile No.	Sample No.	Horizon	Depth (cm.)	Particle-Size Analysis (%) AmS.	AmSi.	C.	ISi.	Texture	ISi./C. Ratio	pH 1:2.5 H_2O	Free Fe_2O_3 (%)	Bulk Density (g./cc.)	Moisture Content (%)	Index of Structure
34	QU266	A1	0-20	23	28	49	24	C	0.49	5.15	6.5	..	..	..
	QU267	B1t	20-40	15	19	66	18	C	0.27	5.25	8.5	..	..	..
	QU268	B21t	40-58	13	12	75	11	C	0.15	5.25	9.1	..	..	..
	QU269	B22t	58-88	13	10	77	10	C	0.13	5.05	9.2	..	..	..
	QU270	B23	88-120	13	7	80	5	C	0.06	5.35	8.7	..	..	..
	QU271	B24	120-158	15	8	77	8	C	0.10	5.25	7.2	..	..	..
	QU272	IIB21tb	158-208	17	10	73	10	C	0.14	5.2	12.4	..	..	..
	QU273	IIB22tb	208-225	18	14	68	11	C	0.16	5.2	12.6	..	..	..
	QU274	IIB23tb	225-295	22	17	61	14	C	0.23	5.3	12.0	..	..	..
	QU275	IIB24b	295-378	19	19	62	14	C	0.23	5.2	13.0	..	..	..
	QU276	IIC1b	378-448	15	21	64	18	C	0.28	5.25	3.4	..	..	..
	QU277	IIC2b	448-598	22	26	52	22	C	0.42	5.05	8.7	..	..	..
	QU278	IIC3b	598-868+	21	32	47	26	C	0.55	5.2	8.5	..	..	..

TABLE 20.--Soils on Tilted Fault-Block Ridge II in the Piedmont Province

Profile No.	Sample No.	Horizon	Depth (cm.)	Particle-Size Analysis (%) AmS.	AmSi.	C.	ISi.	Texture	ISi./C. Ratio	pH 1:2.5 H_2O	Free Fe_2O_3 (%)	Bulk Density (g./cc.)	Moisture Content (%)	Index of Structure
7	QU 52	A1	0-18	70	20	10	15	SL	1.50	5.3	6.1	0.59	..	..
	QU 53	A3t	18-38	26	25	49	21	C	0.43	5.0	6.9	0.77	41	..
	QU 54	B21t	38-78	20	14	66	13	C	0.20	5.0	7.2	0.79	44	..
	QU 55	IIB22t	78-98	16	13	71	12	C	0.17	5.4	7.4	..	..	..
	QU 56	IIB23t	98-108+	20	11	69	9	C	0.13	5.5	7.8	0.81	47	..
11	QU 77	Ap	0-15	41	20	39	15	CL	0.38	5.1	7.9	0.81	45	..
	QU 78	B21t	15-30	27	14	59	11	C	0.19	5.1	8.2	0.81	..	..
	QU 79	B22t	30-58	27	5	68	4	C	0.06	4.8	8.0	0.72	49	..
	QU 80	B23t	58-88	32	2	66	1	C	0.02	4.7	7.3	0.81	74	..
	QU 81	B24t	88-120+	30	8	62	7	C	0.11	4.5	8.4	0.92	..	..
12	QU 82	A1	0-8	32	22	46	17	C	0.37	4.4	7.8	0.65	36	..
	QU 83	B21	8-30	18	25	57	19	C	0.33	5.1	8.3	0.89	36	..
	QU 84	B22t	30-73	34	24	42	18	C	0.43	5.0	7.3	0.99	36	..
	QU 85	IIA3tb	73-98	28	24	48	19	C	0.40	4.5	6.3	0.85	..	..
	QU 86	IIB1tb	98-118	26	27	47	20	C	0.43	4.5	6.3	0.82	40	99.1
	QU 87	IIB21tb	118-135	23	20	57	15	C	0.26	4.5	7.7	0.79	44	99.3
	QU 88	IIB22tb	135-160	22	14	64	12	C	0.19	5.0	6.9	0.82	46	99.2
	QU 89	IIB23tb	160-188+	33	8	59	7	C	0.11	5.0	7.0	0.70	48	99.4

TABLE 20.--Continued

Profile No.	Sample No.	Horizon	Depth (cm.)	Particle-Size Analysis (%) AmS.	AmSi.	C.	ISi.	Texture	ISi./C. Ratio	pH 1:2.5 H_2)	Free Fe_2O_3 (%)	Bulk Density (g./cc.)	Moisture Content (%0	Index of Structure
14	QU 99	A1	0-30	34	24	42	19	C	0.45	5.1	7.4	0.69	51	..
	QU100	B1t	30-50	24	17	59	17	C	0.29	5.5	7.1	0.74	50	..
	QU101	B21t	50-75	26	13	61	10	C	0.16	5.4	8.6	0.70	..	..
	QU102	B22t	75-98+	24	11	65	10	C	0.15	5.3	9.2	0.97	..	..
17	QU121	B21t	0-40	19	14	67	9	C	0.13	5.2	8.3	0.81	43	..
	QU122	B22t	40-115	18	10	72	9	C	0.13	5.1	5.9	0.85	42	..
	QU123	B23	115-158	22	9	69	8	C	0.12	5.0	7.4	0.77	48	..
	QU124	B24	158-185+	17	10	73	9	C	0.12	5.0	7.4	0.83	47	..
19	QU131	A1	0-10	15	42	43	33	SiC	0.77	4.9	6.4	0.77	..	..
	QU132	B1t	10-30	..	..	..	..	..	..	..	..	0.86	33	..
	QU133	B21t	30-55	11	20	69	18	C	0.26	5.4	6.6	0.90	..	..
	QU134	B22t	55-88	17	10	73	8	C	0.11	5.0	6.7	0.81	..	..
	QU135	B23t	88-120	21	13	66	12	C	0.18	5.4	6.3	0.86	..	..
	QU136	IIA3tb	120-148	19	59	22	57	Si	2.59	5.1	6.5	0.94	48	..
	QU137	IIB21tb	148-158+	19	26	55	24	C	0.44	5.0	6.6	0.87	..	..
20	QU139	Ap	0-13	19	25	56	20	C	0.36	5.0	6.9	0.72	53	..
	QU140	B1t	13-43	25	19	56	16	C	0.29	5.1	7.8	0.85	39	..
	QU141	B21t	43-58	9	22	69	20	C	0.29	4.8	8.2	0.92	..	..
	QU142	B22t	58-80	13	13	74	11	C	0.15	4.6	7.9	0.87	44	..
	QU143	B23t	80-113	10	21	69	18	C	0.26	4.6	7.0	0.87	40	..
	QU144	B3t	113-145+	23	24	53	21	C	0.40	4.6	5.7	0.87	42	..

TABLE 20.--Continued

Profile No.	Sample No.	Horizon	Depth (cm.)	Particle-Size Analysis (%) AmS.	AmSi.	C.	ISi.	Texture	ISi./C. Ratio	pH 1:2.5 H_2O	Free Fe_2O_3 (%)	Bulk density (g./cc.)	Moisture Content (%)	Index of Structure
32	QU255	A1	0-3	31	36	33	23	CL	0.70	5.45	8.2	..	..	..
	QU256	A3	3-25	21	36	43	35	C	0.81	5.3	9.0	..	..	..
	QU257	IIB21t	25-48	13	15	72	11	C	0.15	5.55	8.3	..	..	..
	QU258	IIB22t	48-83	11	13	76	10	C	0.13	5.2	8.5	..	..	..
	QU259	IIB23t	83-110	10	10	80	9	C	0.12	5.0	8.7	..	..	..
	QU260	IIB24t	110-133+	11	17	72	12	C	0.17	5.0	9.2	..	..	..
33	QU261	A1	0-28	14	32	54	26	C	0.48	5.65	8.9	..	..	..
	QU262	B21	28-45	9	19	72	15	C	0.21	5.5	7.8	..	..	..
	QU263	B22	45-83	11	13	76	11	C	0.14	5.2	8.5	..	..	..
	QU264	B23	83-110	13	11	76	8	C	0.11	4.85	10.1	..	..	..
	QU265	B24	110-148+	13	9	78	9	C	0.12	4.8	9.8	..	..	..

TABLE 21.--Soils on Tilted Fault-Block Ridge III in the Piedmont Province

Profile No.	Sample No.	Horizon	Depth (cm.)	Particle-Size Analysis (%) AmS.	AmSi.	C.	ISi.	Texture	ISi./C. Ratio	pH 1:2.5 H_2O	Free Fe_2O_3 (%)	Bulk Density (g./cc.)	Moisture Content (%)	Index of Structure
5	QU 29	Ap	0-18	24	28	48	23	C	0.48	5.1	6.9	0.81	44	..
	QU 30	B21t	18-55	18	14	68	11	C	0.16	5.3	7.7	0.97	46	..
	QU 31	B22	55-90	22	14	64	12	C	0.19	5.3	9.0	0.99	46	..
	QU 32	IIB23	90-115	25	10	65	6	C	0.09	5.0	8.1	1.00	44	..
	QU 33	IIB3t	115-133	17	29	54	22	C	0.41	4.9	6.4	0.93	40	..
	QU 34	IIC	133-200+	26	29	45	22	C	0.49	4.9	5.8	0.95	42	..
	QU 35	Bulk	..	26	65	9	55	SiL	6.11	4.7	1.8	0.70	68	..
	QU 36	Bulk	..	28	24	48	21	C	0.44	4.8	8.6	0.69	64	..
	QU 37	Bulk	..	32	57	11	45	SiL	4.09	5.0	..	0.76	67	..
	QU 38	Bulk	..	54	46	0	18	SL	..	6.2	0.8	..	..	..
	QU 39	Bulk	..	35	56	9	42	SiL	4.67	5.1	..	..	..	..
23	QU164	A1	0-13	53	20	27	13	SCL	0.48	5.75	6.3	0.69	57	..
	QU165	B1t	13-30	20	28	52	23	C	0.44	5.8	7.3	0.69	61	..
	QU166	B21	30-68	12	22	66	19	C	0.29	5.95	7.8	0.80	49	..
	QU167	B22	68-105	16	16	68	13	C	0.19	6.0	7.9	0.80	49	..
	QU168	B23	105-133	15	17	68	14	C	0.21	5.2	8.5	0.82	45	..
	QU169	B3	133-163+	17	25	58	18	C	0.31	5.4	8.5	0.74	37	..

TABLE 21.--Continued

Profile No.	Sample No.	Horizon	Depth (cm.)	Particle-Size Analysis (%) AmS.	AmSi.	C.	ISi.	Texture	ISi./C. Ratio	pH 1:2.5 H_2O	Free Fe_2O_3 (%)	Bulk density (g./cc.)	Moisture Content (%)	Index of Structure
24	QU171	Ap	0-13	44	29	27	23	L	0.85	5.4	6.1	0.66	55	..
	QU172	B21t	13-28	14	19	67	16	C	0.24	5.6	7.4	0.74	51	..
	QU173	B22	28-50	20	15	65	11	C	0.17	4.9	5.8	0.72	57	..
	QU174	B23	50-83	11	18	71	15	C	0.21	4.8	7.3	0.70	54	..
	QU175	B24	83-115	23	13	64	11	C	0.17	4.8	7.9	0.77	48	..
	QU176	IIA2b	115-133	32	13	55	11	C	0.20	5.1	7.1	0.65	62	..
	QU177	IIB21b	133-208	12	21	67	20	C	0.30	5.05	8.0	0.77	50	..
	QU178	IIB22tb	208-318	24	14	62	13	C	0.21	4.9	8.3	0.90	45	..
	QU179	IIB3tb	318-403+	25	24	51	20	C	0.39	4.9	8.4	0.69	54	..
31	QU238	A1	0-35	32	28	40	21	CL	0.53	5.15	7.3	..	..	..
	QU239	B1	35-55	22	28	50	23	C	0.46	5.15	8.1	..	..	..
	QU240	B21	55-80	22	22	56	18	C	0.32	5.1	6.4	..	..	..
	QU241	B22	80-120	20	17	63	14	C	0.22	4.9	7.6	..	..	..
	QU242	B23t	120-166	15	5	80	5	C	0.06	5.1	8.0	..	..	..
	QU243	B3	166-203	25	24	51	19	C	0.37	4.9	9.8	..	..	..
	QU244	IIB21tb1	203-253	24	15	61	12	C	0.20	4.8	7.9	..	..	..
	QU245	IIB22tb1	253-308	20	12	68	7	C	0.10	4.8	6.0	..	..	..
	QU246	IIB3cnb1	308-348	26	19	55	13	C	0.24	4.85	5.8	..	..	..
	QU247	IIIB1cnb2	348-368	27	25	48	20	C	0.42	4.9	4.8	..	..	..
	QU248	IIIB21tcnb2	368-433	18	16	66	13	C	0.20	4.85	5.3	..	..	..
	QU249	IIIB22tcnb2	433-465	17	17	66	12	C	0.18	4.8	4.9	..	..	..
	QU250	IIICcnb2	465-498	21	26	53	22	C	0.42	5.0	3.0	..	..	..
	QU251	IVB21tcnb3	498-558	19	28	53	22	C	0.42	4.75	7.5	..	..	..
	QU252	IVB22tcnb3	558-688	25	32	43	24	C	0.56	4.85	7.7	..	..	..
	QU253	IVB3tcnb3	688-863	28	39	33	31	CL	0.94	4.8	6.7	..	..	..
	QU254	IVCtcnb3	863-1113+	30	34	36	27	CL	0.75	4.9	6.6	..	..	..

TABLE 22.--Soils on Alluvial/Laharic Fans in the Piedmont Province

Profile No.	Sample No.	Horizon	Depth (cm.)	Particle-Size Analysis (%) AmS.	AmSi.	C.	ISi.	Texture	ISi./C. Ratio	pH 1:2.5 H_2O	Free Fe_2O_3 (%)	Bulk Density (g./cc.)	Moisture Content (%)	Index of Structure
8	QU 57	A1	0-33	40	33	27	23	L	0.85	5.1	5.5	0.77	..	..
	QU 58	IIB21 cn	33-60	29	27	44	21	C	0.48	5.1	6.0	0.73	59	..
	QU 59	IIIB22cn	60-83	40	23	37	18	CL	0.49	5.1	5.4	..	..	..
	QU 60	IIIC1 cn	83-110	71	19	10	13	SL	1.30	5.1	5.5	0.70	64	..
	QU 61	IIIC2	110-143	84	12	4	7	LS	1.75	4.9	5.5	0.69	71	..
	QU 62	IIIC3	143-163	68	19	13	13	SL	1.00	4.9	9.0	0.74	59	..
	QU 63	IIIC4	163-175+	88	10	2	7	S	3.50	4.8	8.4	0.68	71	..
16	QU115	A1	0-13	64	24	12	17	SL	1.42	4.6	6.3	..	..	75
	QU116	A2	13-25	64	26	10	16	SL	1.60	5.2	5.9	0.65	..	83
	QU117	B1	25-40	51	29	20	19	L	0.95	5.2	6.4	0.73	48	91
	QU118	B21	40-60	48	24	28	19	SCL	0.68	5.7	6.8	0.70	44	96
	QU119	B22	60-93	40	20	40	16	CL	0.40	5.2	5.9	0.61	52	99.8
	QU120	B23	93-108+	32	21	47	17	C	0.36	5.2	7.3	0.53	..	100
22	QU160	A1	0-8	44	36	20	26	L	1.30	5.4	7.8	0.77	50	..
	QU161	A3t	8-28	61	29	10	15	SL	1.50	5.7	8.4	0.78	48	99.2
	QU162	IIB1	28-60	49	25	26	19	L	0.73	5.5	8.2	0.71	65	99.8
	QU163	IIB2	60-105	43	19	38	20	CL	0.53	5.4	8.6	..	..	99.7

TABLE 22.--Continued

Profile No.	Sample No.	Horizon	Depth (cm.)	Particle-Size Analysis (%) AmS.	AmSi.	C.	ISi.	Texture	ISi./C. Ratio	pH 1:2.5 H_2O	Free Fe_2O_3 (%)	Bulk Density (g./cc.)	Moisture Content (%)	Index of Structure
4	QU 23	A1	0-20	66	17	17	11	SL	0.65	4.8	7.4	..	..	..
	QU 24	B1	20-45	29	23	48	19	C	0.40	5.0	8.7	..	..	..
	QU 25	B21	45-80	30	19	51	16	C	0.31	4.9	9.0	..	..	..
	QU 26	B22	80-123	29	19	52	15	C	0.29	4.9	9.3	..	..	..
	QU 27	IIB23	123-163	26	22	52	20	C	0.38	4.9	10.3	..	..	..
	QU 28	IIC	163-203+	25	38	37	29	CL	0.78	4.8	8.8	..	..	..
30	QU232	A1	0-18	38	26	36	21	CL	0.58	4.9	6.7	..	..	..
	QU233	B1	18-45	26	23	51	19	C	0.37	5.15	8.0	..	..	..
	QU234	B21	45-73	18	22	60	20	C	0.33	5.15	9.4	..	..	..
	QU235	B22	73-93	21	22	57	18	C	0.32	5.3	9.2	..	..	..
	QU236	IIB23cn	93-125	21	23	56	20	C	0.36	5.4	9.4	..	..	..
	QU237	IIB3cn	125-180+	25	27	48	21	C	0.44	5.15	10.3	..	..	..

TABLE 23.--Soils on Cinder Cones and Associated Pyroclastic Deposits in the Piedmont Province

Profile No.	Sample No.	Horizon	Depth (cm.)	Particle-Size Analysis (%) AmS.	AmSi.	C.	ISi.	Texture	ISi./C. Ratio	pH 1:2.5 H_2O	Free Fe_2O_3 (5)	Bulk Density (g./cc.)	Moisture Content (%)	Index of Structure
15	QU105	A1	0-20	34	10	56	9	C	0.16	5.2	9.1	0.73	..	..
	QU106	IIB1t	20-48	49	3	48	2	SC	0.04	5.0	9.6	0.88	43	..
	QU107	IIIB21t	48-75	23	2	75	1	C	0.01	5.0	8.2	0.77	48	..
	QU108	IIIB22t	75-118	7	6	87	6	C	0.07	4.9	9.7	0.73	43	..
	QU109	IIIB23t	118-135+	23	2	75	2	C	0.03	4.7	9.2	0.69	46	..
	QU279	..	Bulk	39	50	11	35	SiL	3.18	7.1	..	..	..	..
3	QU 18	A1	0-25	68	21	11	14	SL	1.27	5.6	6.0	0.60	39	..
	QU 19	B2	25-40	62	30	8	19	SL	2.38	5.2	7.3	0.71	55	..
	QU 20	C	40-58	60	27	13	17	SL	1.31	5.6	4.1	..	..	..
	QU 21	IIB21b	58-120	24	22	54	17	C	0.31	5.0	8.5	0.77	43	..
	QU 22	IIB22tb	120-148+	34	17	49	17	C	0.35	5.5	9.4	0.78	50	..
6	QU 40	Ap	0-35	23	11	66	10	C	0.15	4.9	8.5	0.87	52	..
	QU 41	B21t	35-73	29	11	60	10	C	0.17	4.9	9.4	0.79	53	..
	QU 42	B22t	73-110	31	16	53	13	C	0.25	4.9	10.3	..	..	..
	QU 43	B3	110-145	36	21	43	17	C	0.40	4.9	12.5	0.78	56	..
	QU 44	C1	145-178	32	34	34	28	CL	0.82	5.2	9.4	0.77	43	..
	QU 45	IIC2	178-213	28	36	36	31	CL	0.86	5.1	8.8	..	..	..
	QU 46	IIC3	213-235	25	38	37	33	CL	0.89	5.0	8.0	0.86	45	..
	QU 47	IIC4	235-325+	25	42	33	34	CL	1.03	5.0	6.9	0.89	39	..

TABLE 23.--Continued

Profile No.	Sample No.	Horizon	Depth (cm.)	Particle-Size Analysis (%) AmS.	AmSi.	C.	ISi.	Texture	ISi./C. Ratio	pH 1:2.5 H_2O	Free Fe_2O_3 (%)	Bulk Density (g./cc.)	Moisture Content (%)	Index of Structure
6	QU 48	IIIA1cnb	390-418	26	39	35	35	CL	1.00	5.0	10.7	0.72	50	..
	QU 49	IIIB21b	418-453	28	23	49	17	C	0.35	4.9	7.7	0.80	47	..
	QU 50	IIIB22b	453-470	31	21	48	15	C	0.31	4.9	8.3	0.79	49	..
	QU 51	IIICb	470-493+	35	27	38	20	CL	0.53	4.9	7.2	0.92	43	..
26	QU190	A11	0-15	39	29	32	23	CL	0.72	5.1	6.3	..	..	..
	QU191	A12	15-30	31	33	36	27	CL	0.75	5.0	7.3	..	..	..
	QU192	B1	30-48	21	23	56	21	C	0.38	5.1	6.3	..	..	..
	QU193	B21	48-88	19	24	57	21	C	0.37	5.3	7.9	..	..	..
	QU194	B22	88-123	17	16	67	14	C	0.21	5.2	8.1	..	..	..
	QU195	B23	123-145	14	21	65	12	C	0.18	5.2	7.8	..	..	..
	QU196	B24	145-180	26	12	62	10	C	0.16	5.25	8.3	..	..	..
	QU197	B25	180-215	29	20	51	17	C	0.33	5.25	8.2	..	..	..
	QU198	B26	215-240	33	20	47	17	C	0.36	5.3	8.7	..	..	..
	QU199	B3cn	240-273	31	32	37	25	CL	0.68	5.3	8.7	..	..	..
	QU200	C1	273-298	65	25	10	16	SL	1.60	5.2	7.7	..	..	..
	QU201	IIC2	298-323	11	65	24	43	SiL	1.79	5.1	7.1	..	..	..
	QU202	IIC3	323-415	23	54	23	41	SiL	1.78	5.3	6.9	..	..	..
	QU203	IIC4cn	415-490	20	56	24	45	SiL	1.88	5.3	7.0	..	..	..
	QU204	IIC5cn	490-563	19	57	24	44	SiL	1.83	5.3	6.2	..	..	..
	QU205	IIC6cn	563-613	33	51	16	38	SiL	2.38	5.25	6.2	..	..	..
	QU206	IIC7	613-658	22	59	19	46	SiL	2.42	5.2	5.7	..	..	..
	QU207	IIC8	658-703	35	51	14	38	SiL	2.71	5.1	6.3	..	..	..
	QU208	IIC9cn	703-725	31	47	22	36	L	1.64	5.1	8.1	..	..	..
	QU209	IIC10cn	725-748+	44	44	12	33	L	2.75	5.1	5.0	..	..	..

APPENDIX IV

AGUAS ZARCAS AND QUESADA TOPOGRAPHIC SHEETS

The two topographic sheets are found in the map pocket on the inside of the backcover of the dissertation.